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(54) **APPARATUS FOR PITCH AND YAW ROTATION**

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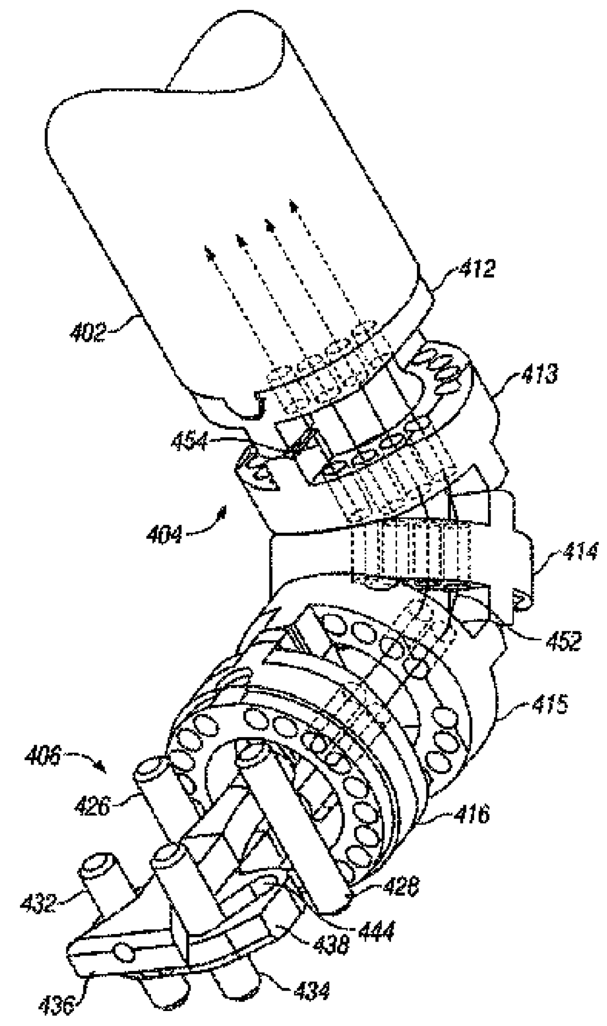
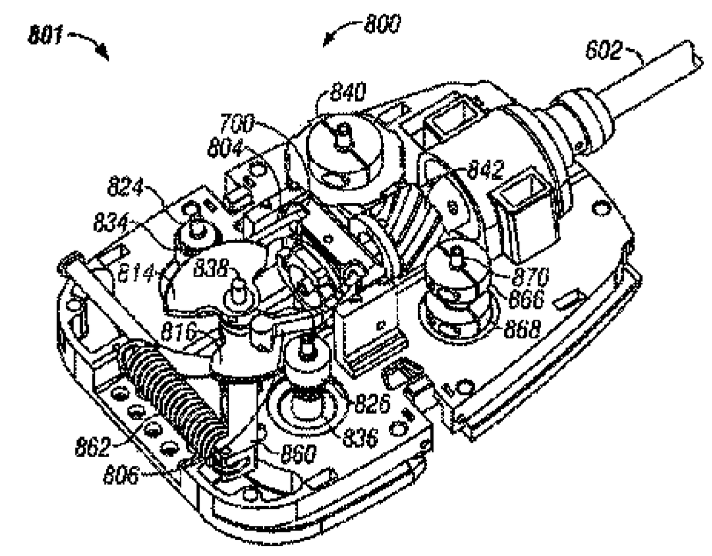
(57) **ABSTRACT**

The present invention is directed to a tool having a wrist mechanism that provides pitch and yaw rotation in such a way that the tool has no singularity in roll, pitch, and yaw. A positively positionable multi-disk wrist mechanism includes a plurality of disks or vertebrae stacked in series. Each vertebra is configured to rotate in pitch or in yaw with respect to each neighboring vertebra. Actuation cables are used to manipulate and control movement of the vertebrae. In specific embodiments, some of the cables are distal cables that extend from a proximal vertebra through one or more intermediate vertebrae to a distal vertebra, while the remaining cables are medial cables that extend from the proximal vertebra to one or more of the intermediate vertebrae. The cables are actuated by a pivoted plate cable actuator mechanism.

16 Claims, 55 Drawing Sheets





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continuation of application No. 13/414,445, filed on Mar. 7, 2012, now Pat. No. 8,911,428, which is a continuation of application No. 12/782,833, filed on May 19, 2010, now Pat. No. 8,142,421, which is a division of application No. 10/980,119, filed on Nov. 1, 2004, now Pat. No. 7,736,356, which is a division of application No. 10/187,248, filed on Jun. 28, 2002, now Pat. No. 6,817,974.

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(58) **Field of Classification Search**

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See application file for complete search history.

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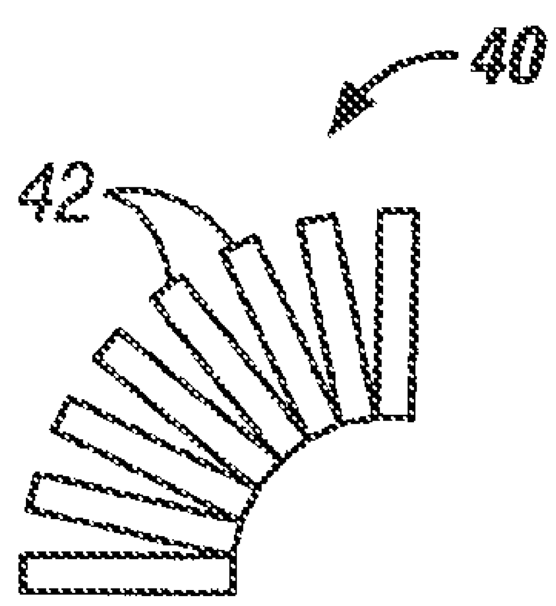


FIG. 1

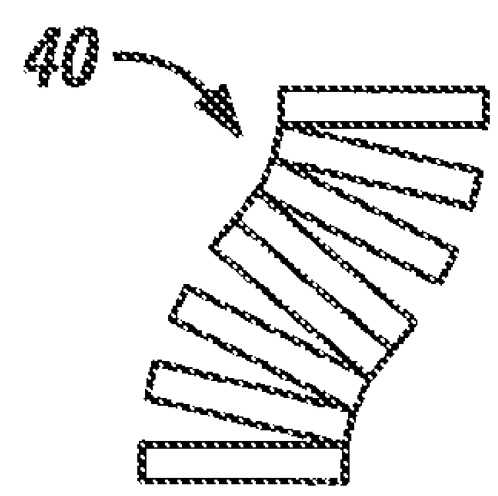
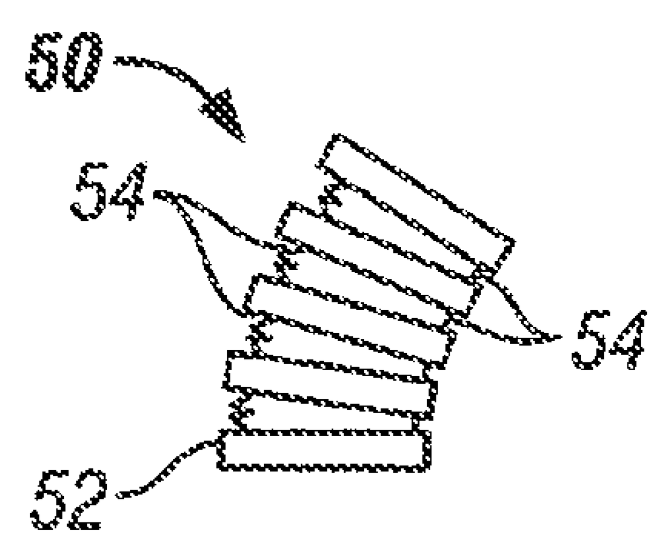


FIG. 2



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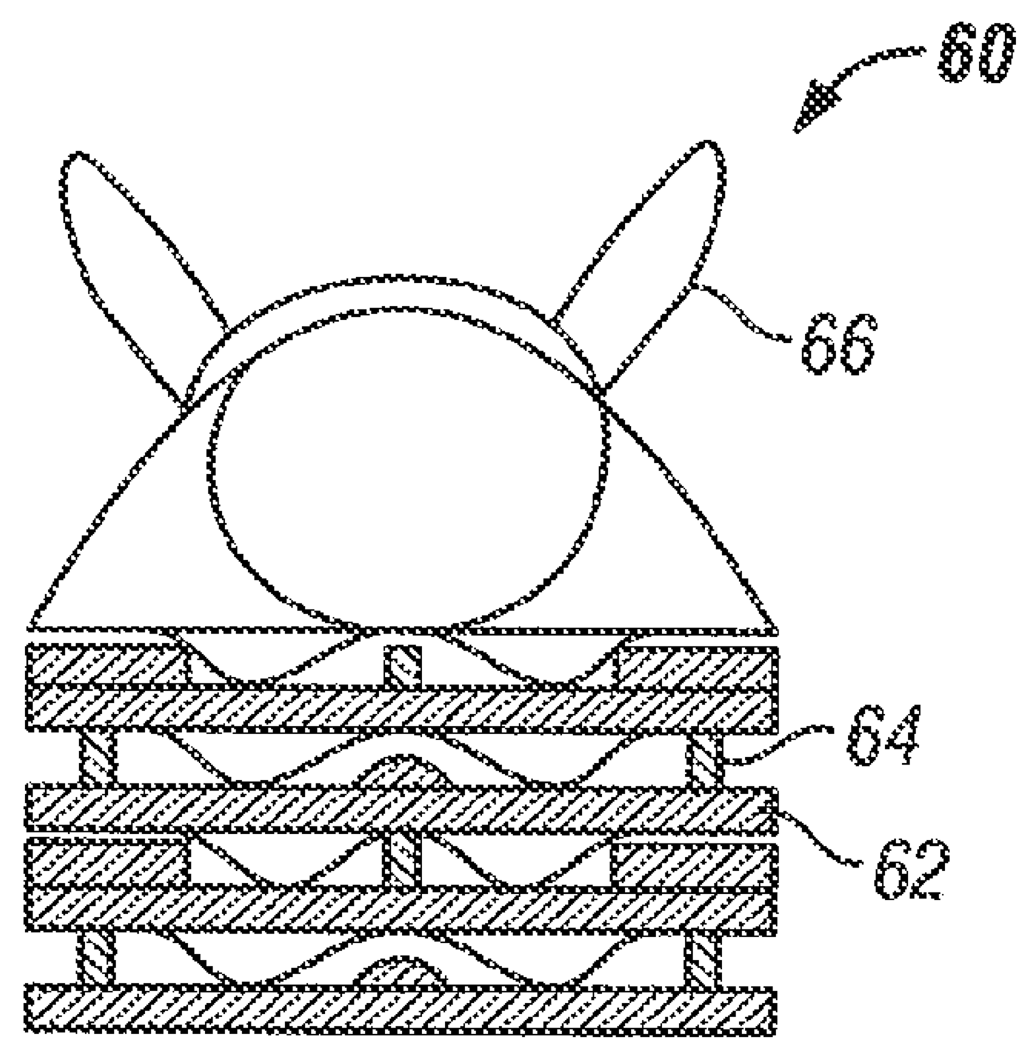

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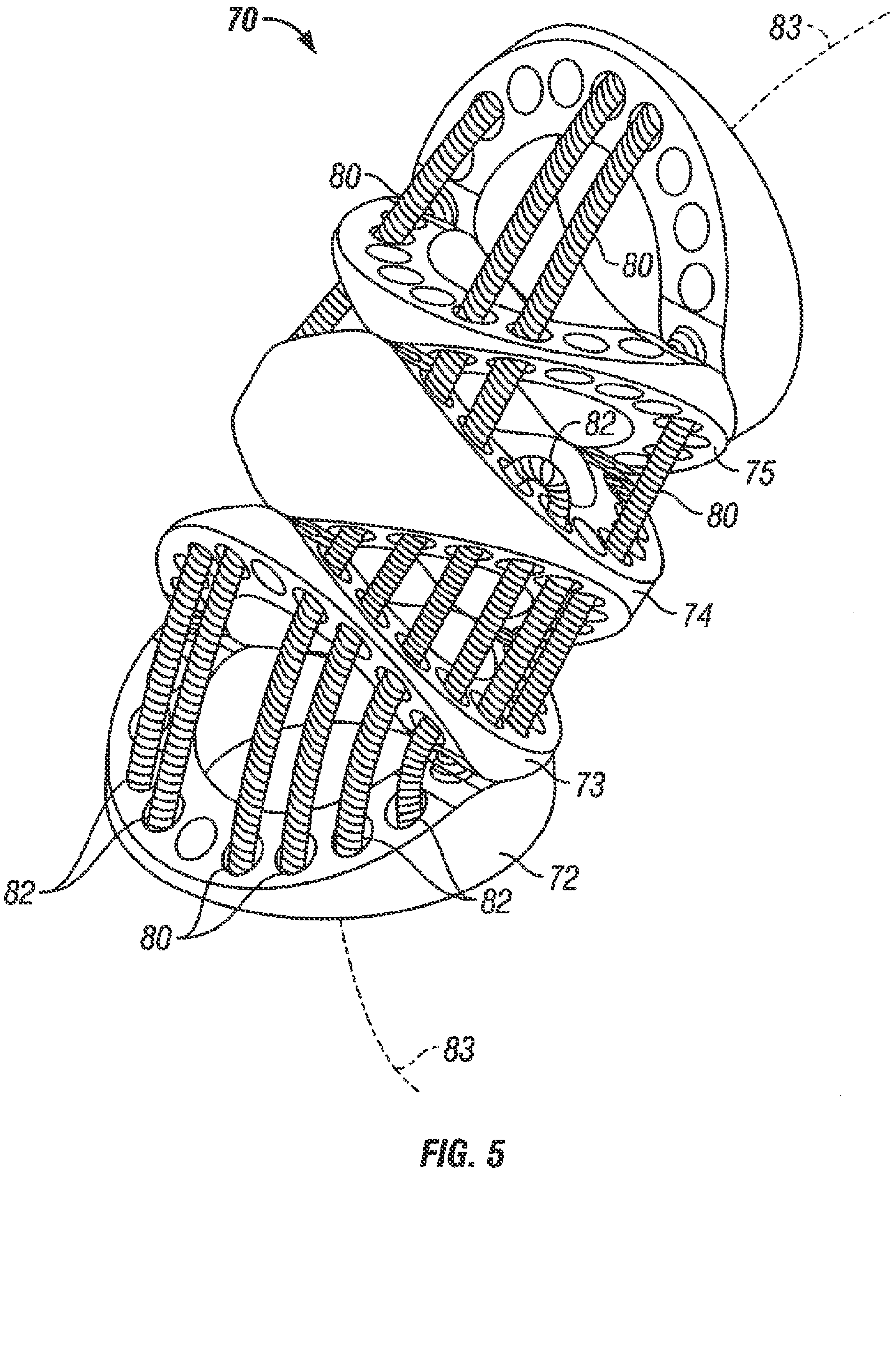


FIG. 5

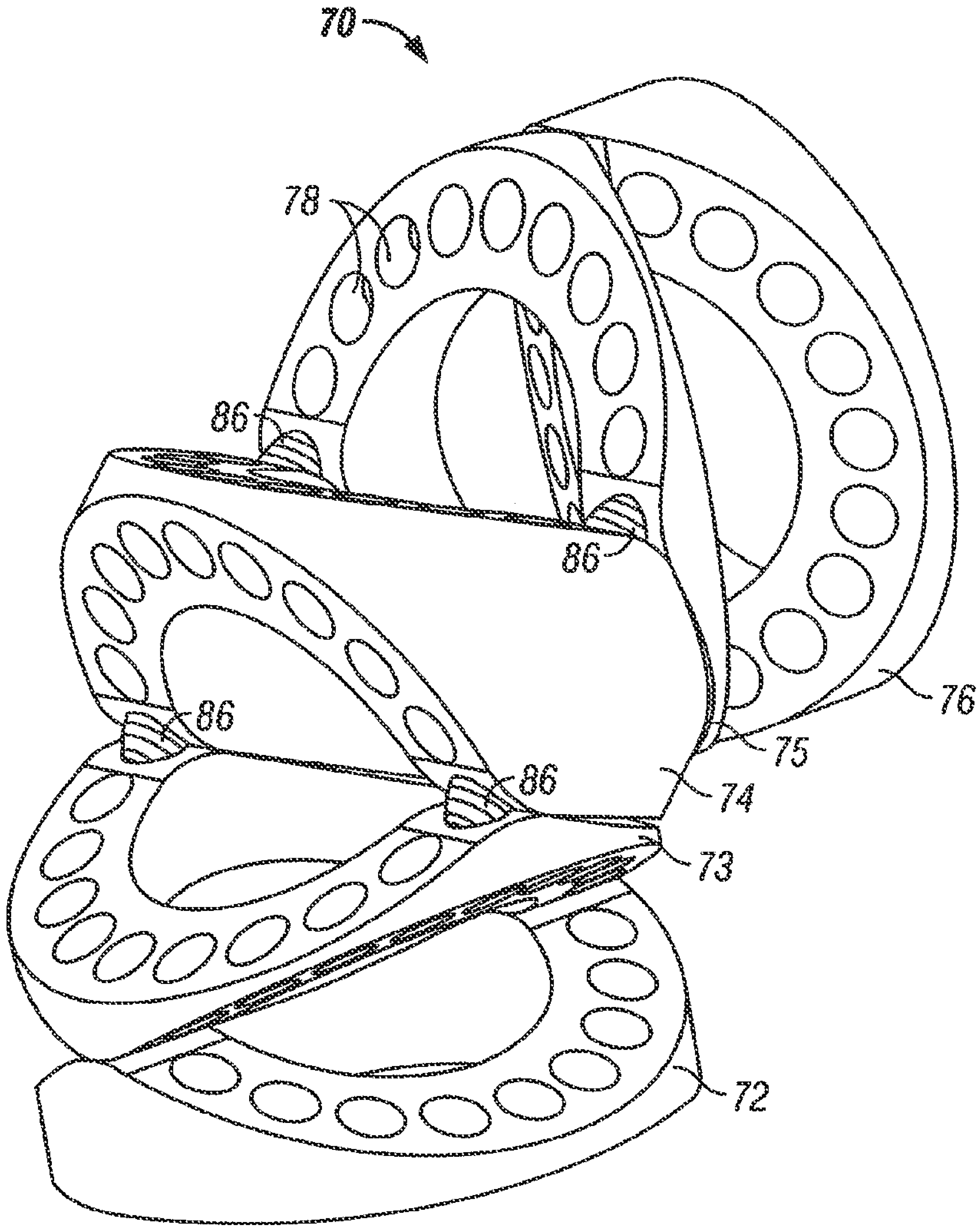
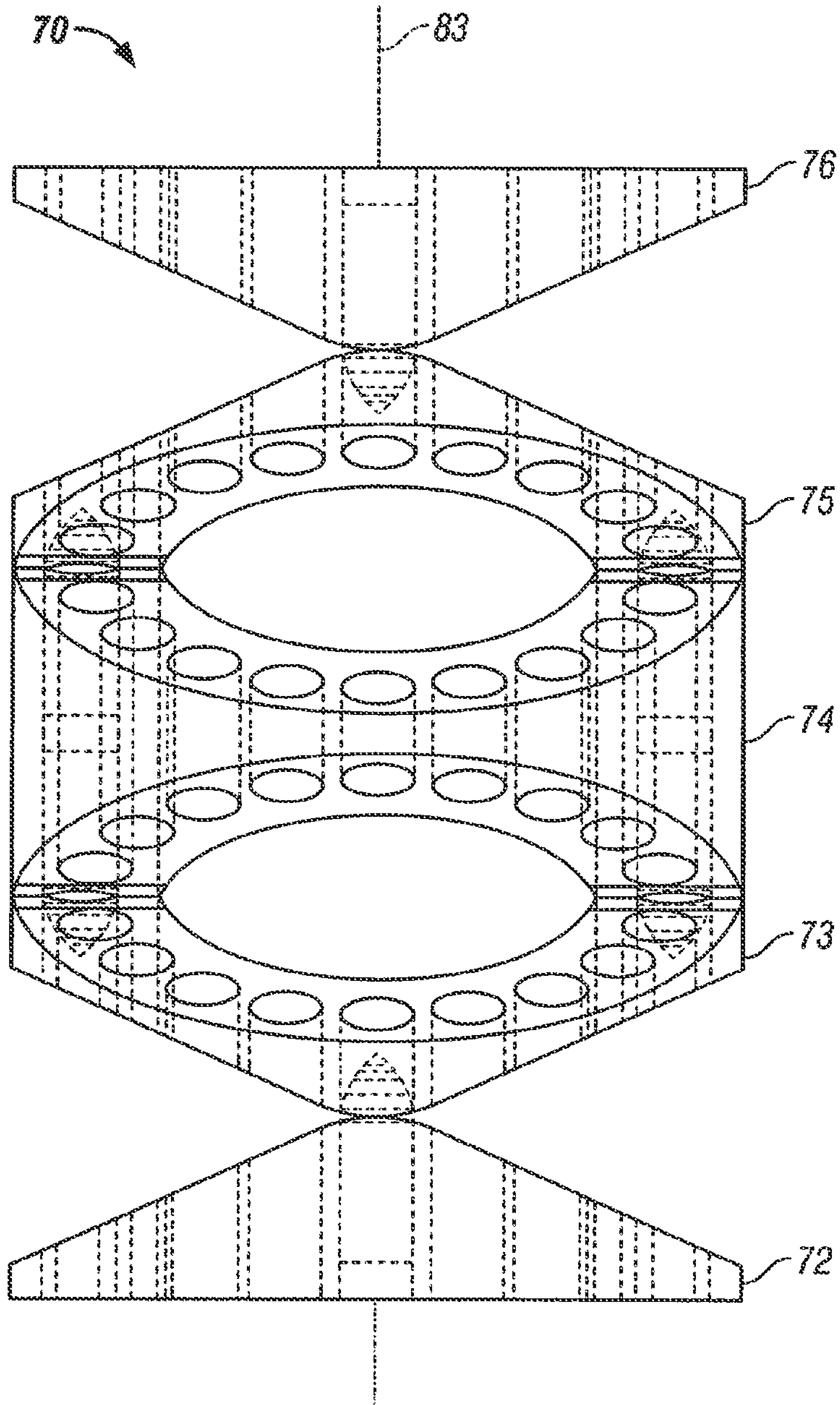


FIG. 6



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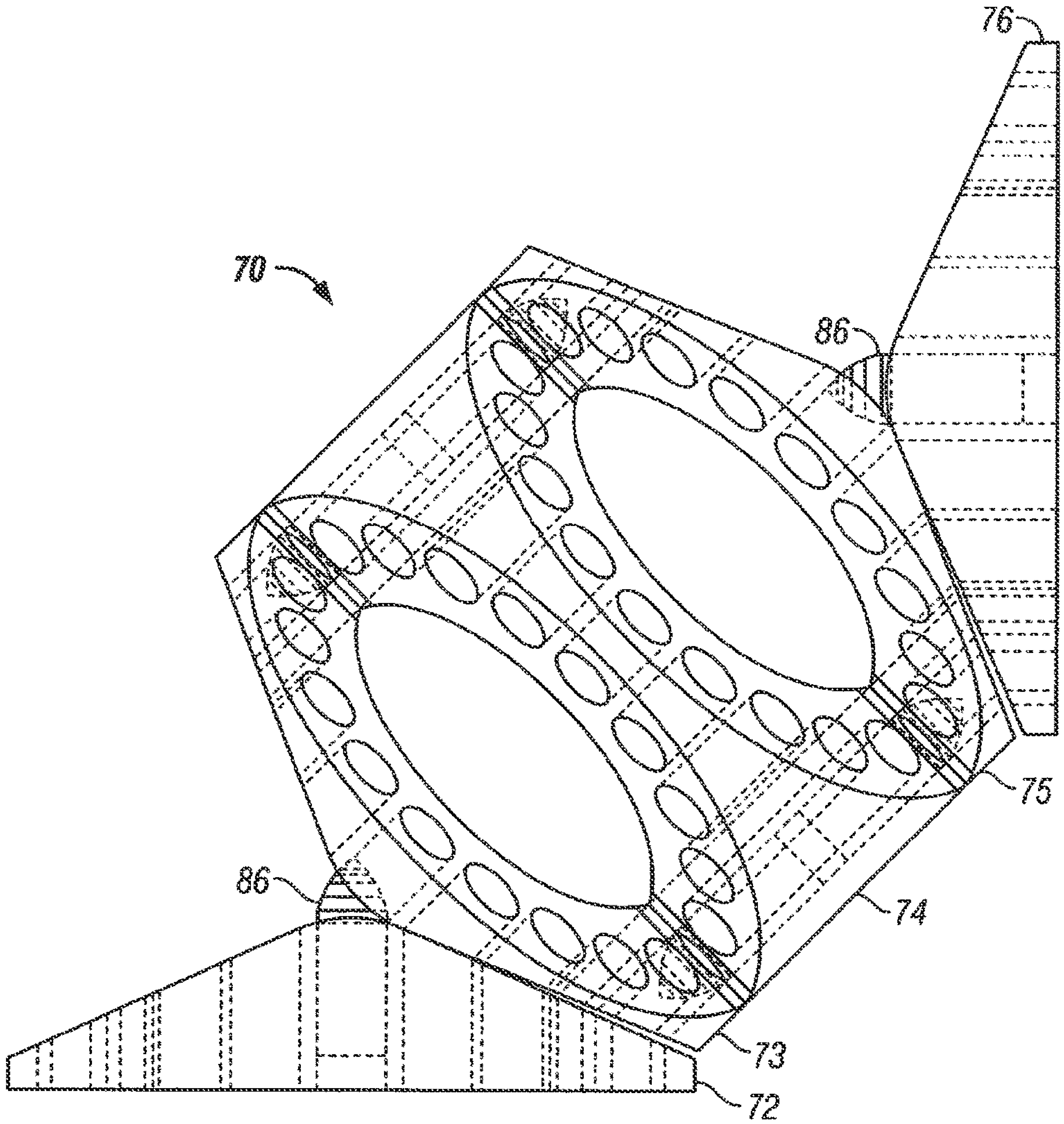


FIG. 8

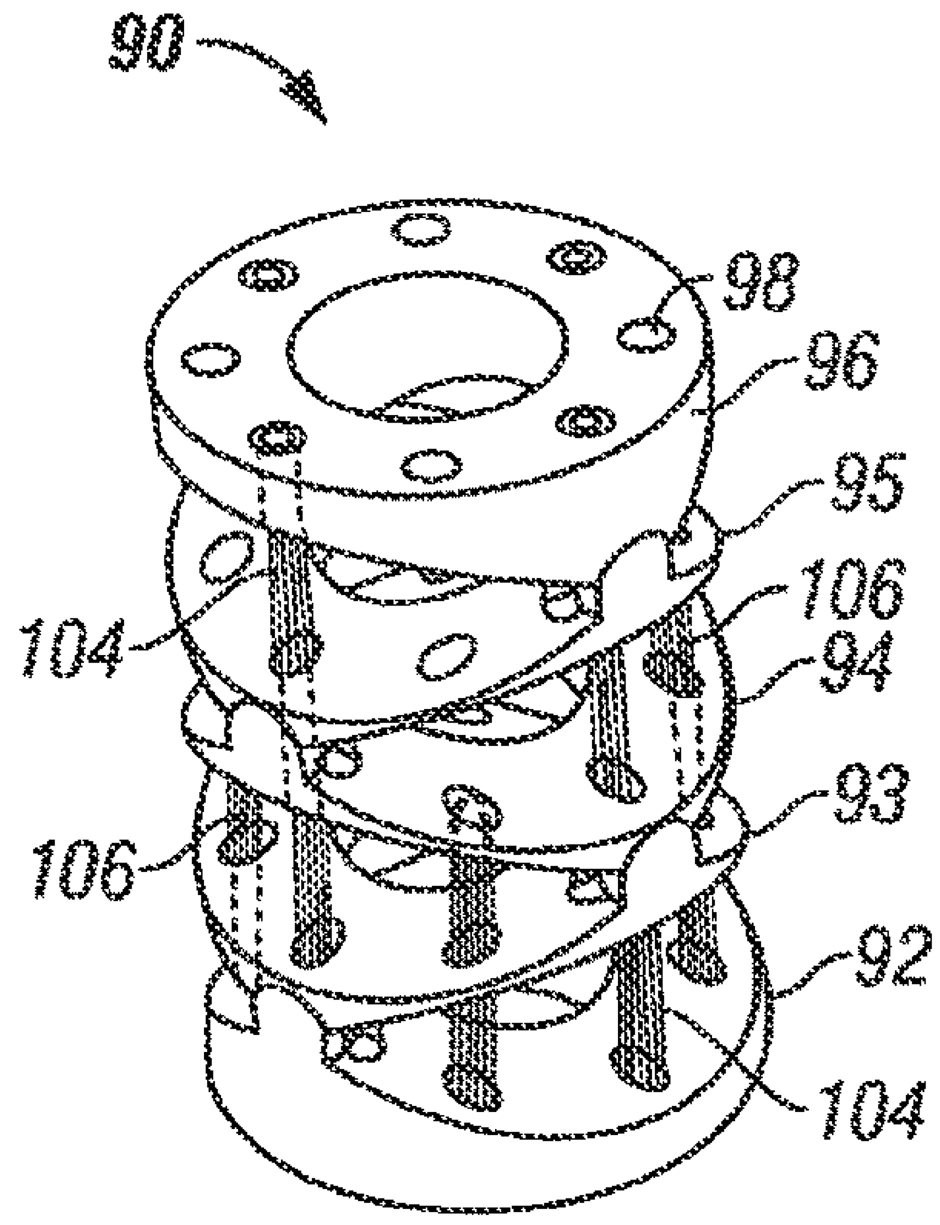


FIG. 9

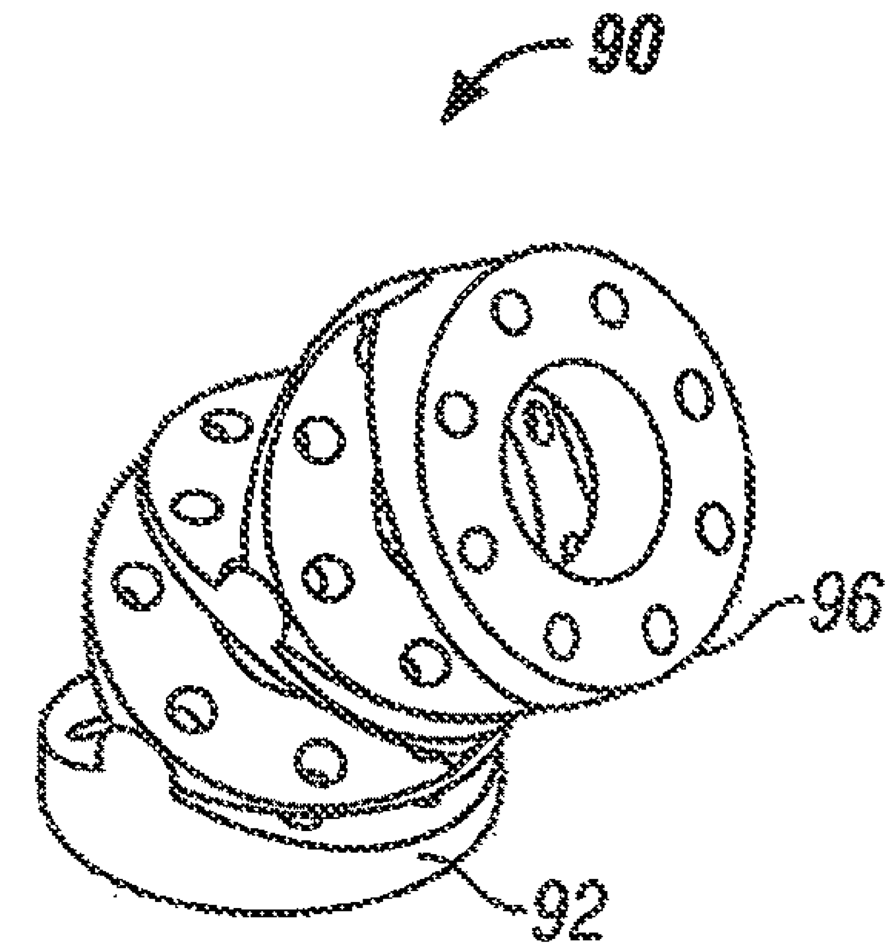


FIG. 10

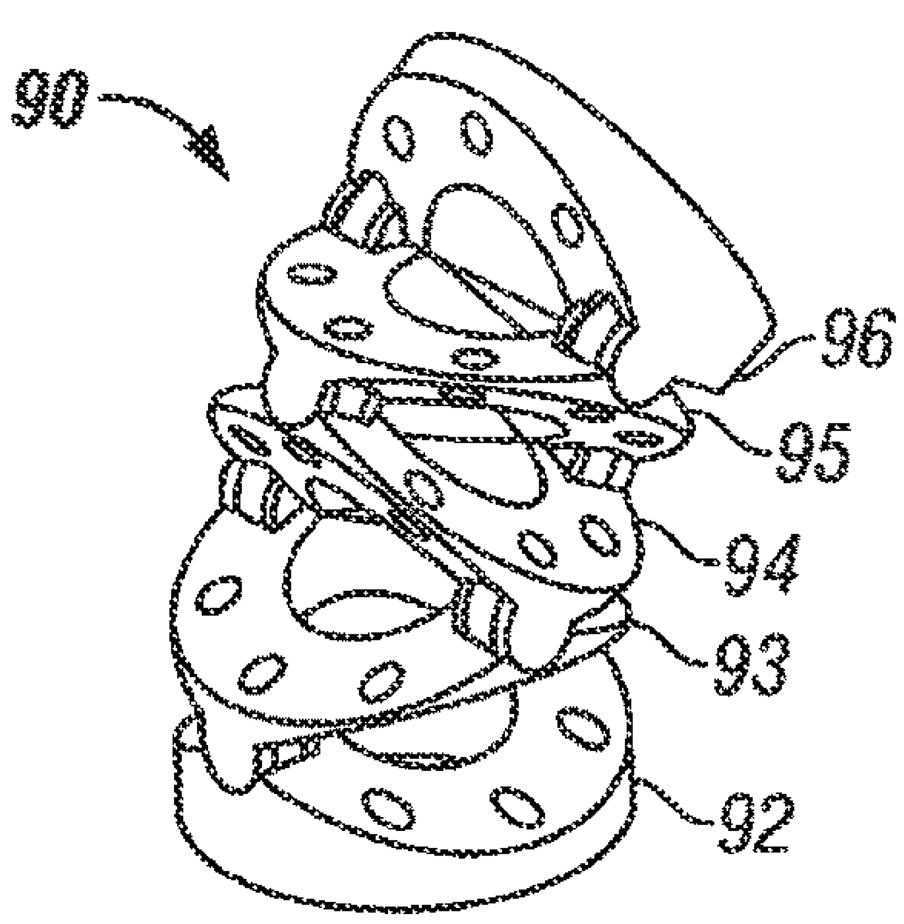
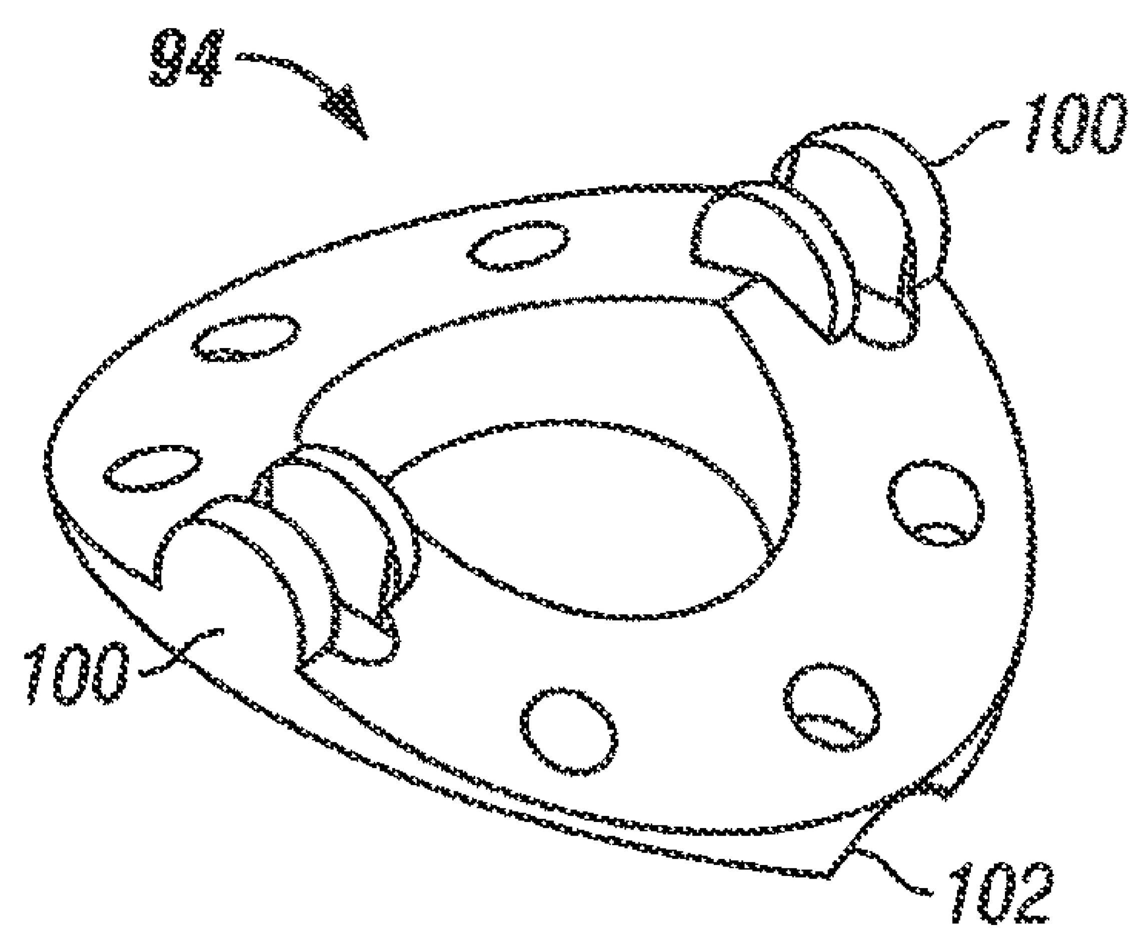


FIG. 11



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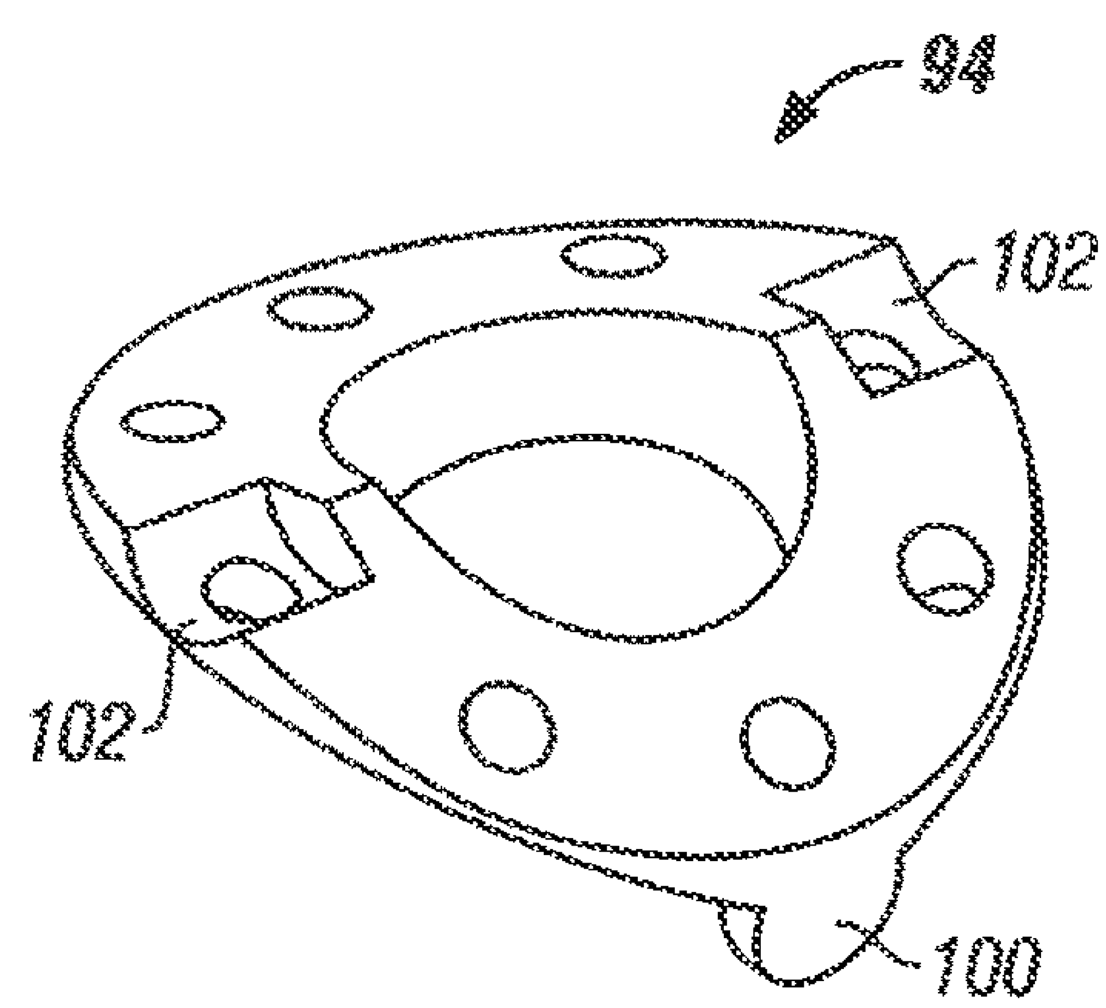

FIG. 13

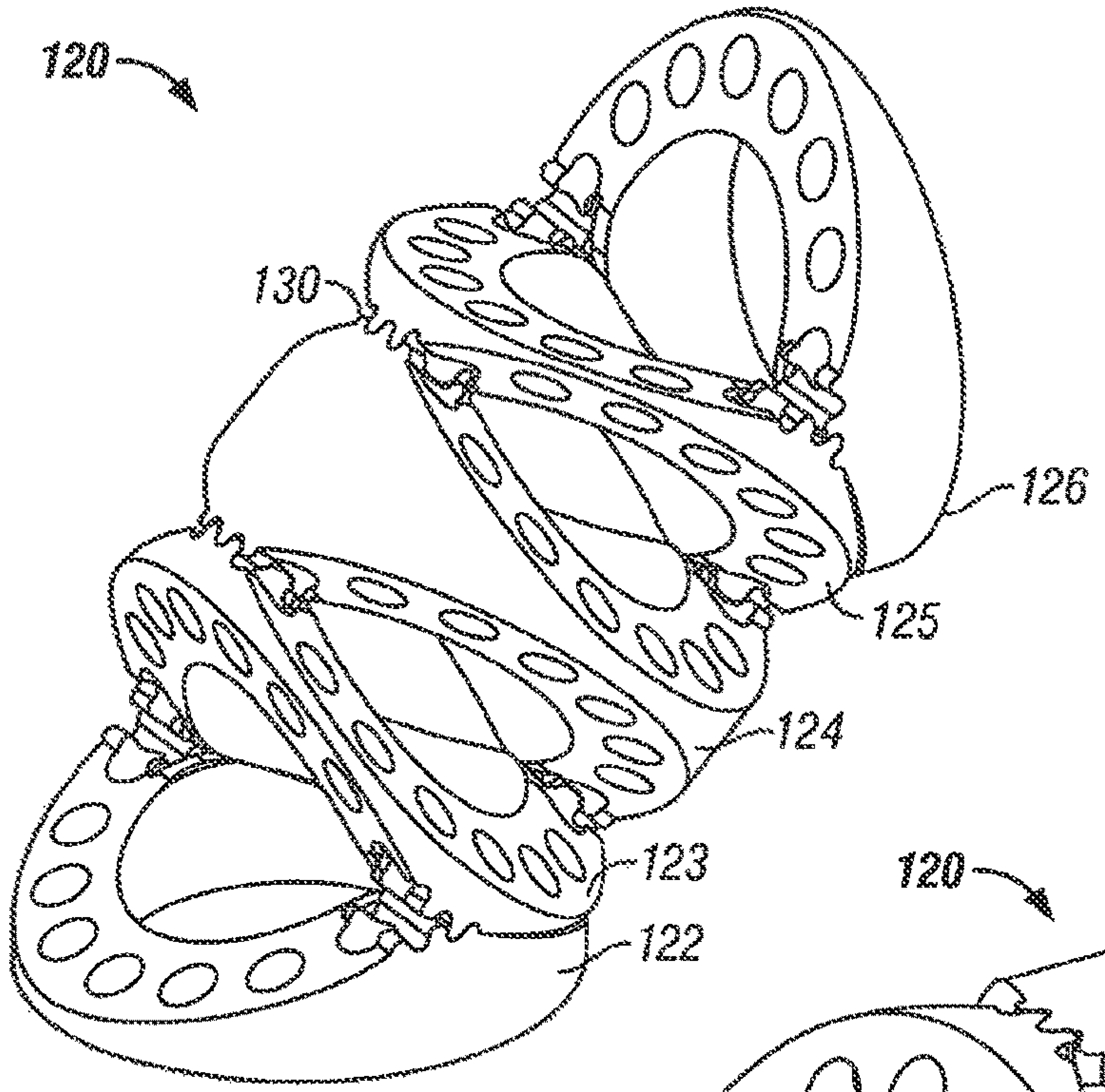

FIG. 14

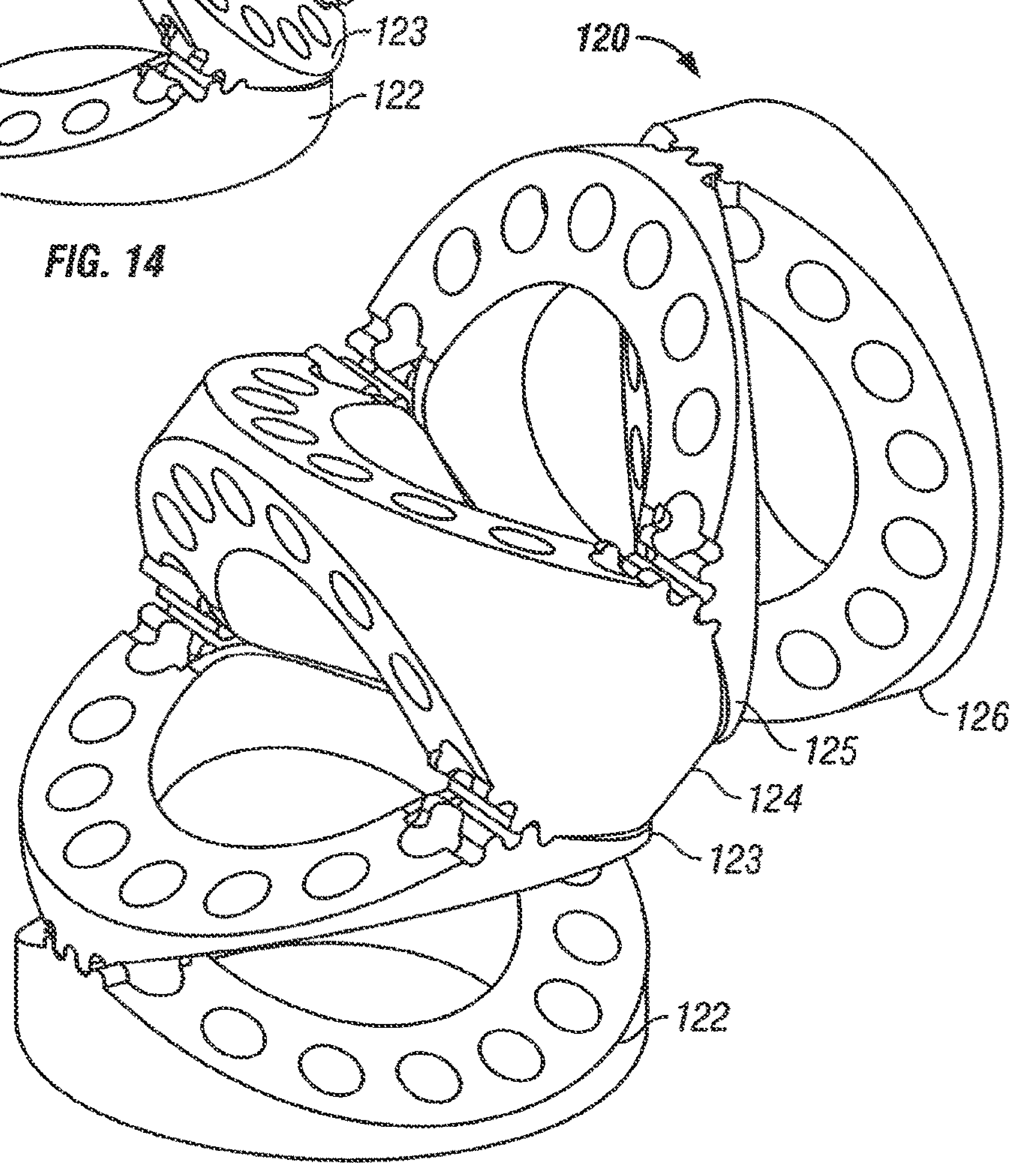

FIG. 15

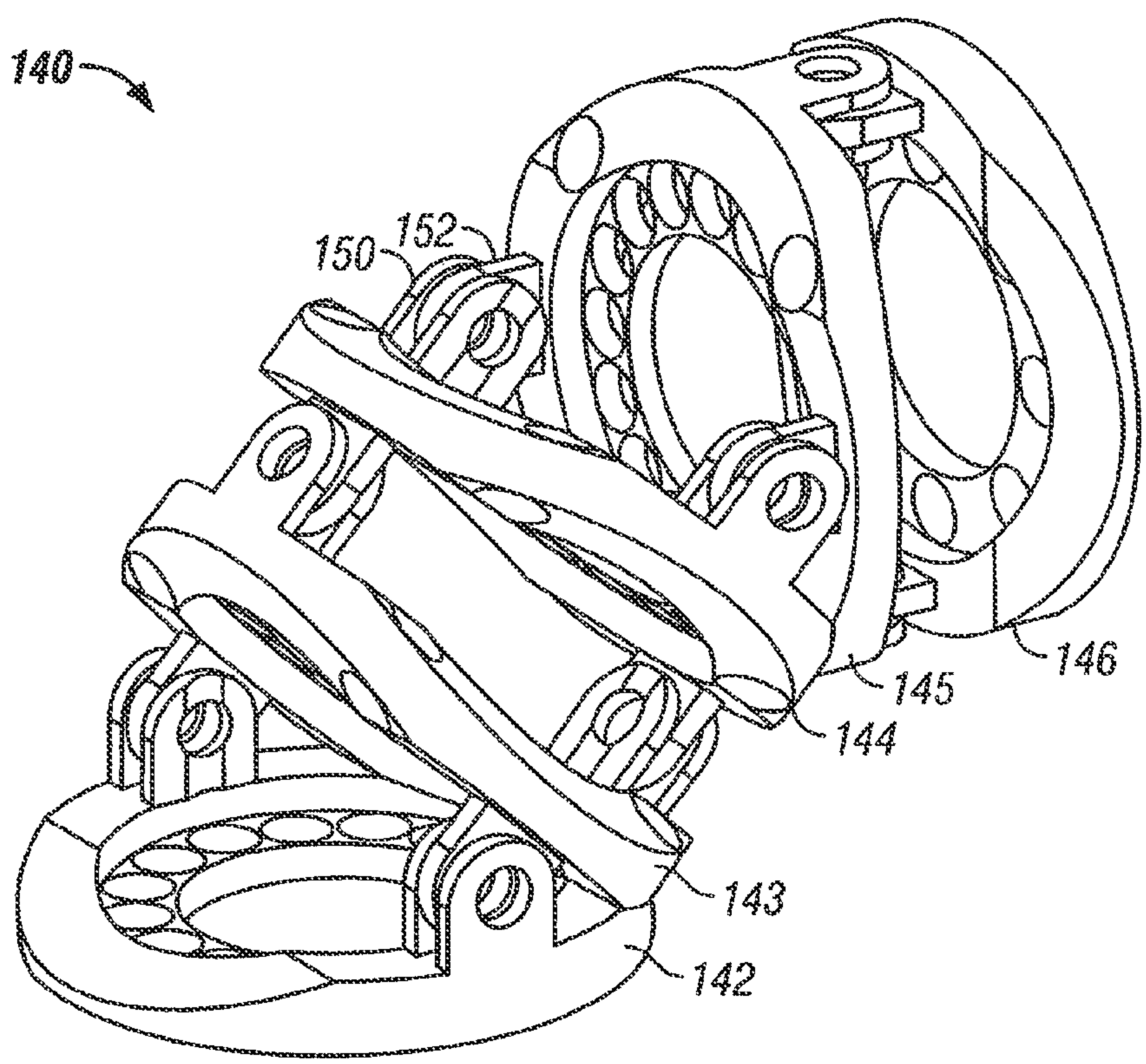

FIG. 16

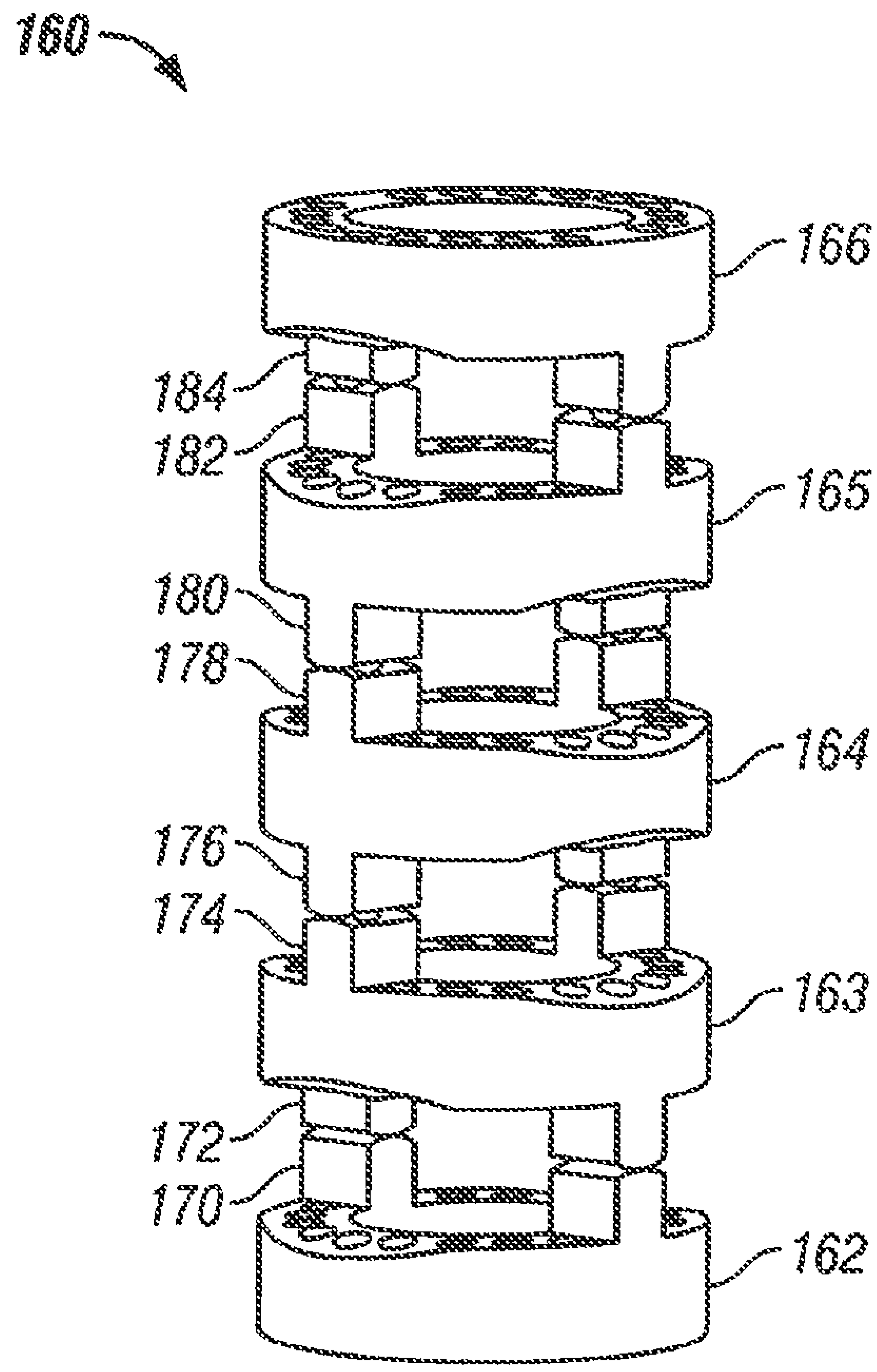

FIG. 17

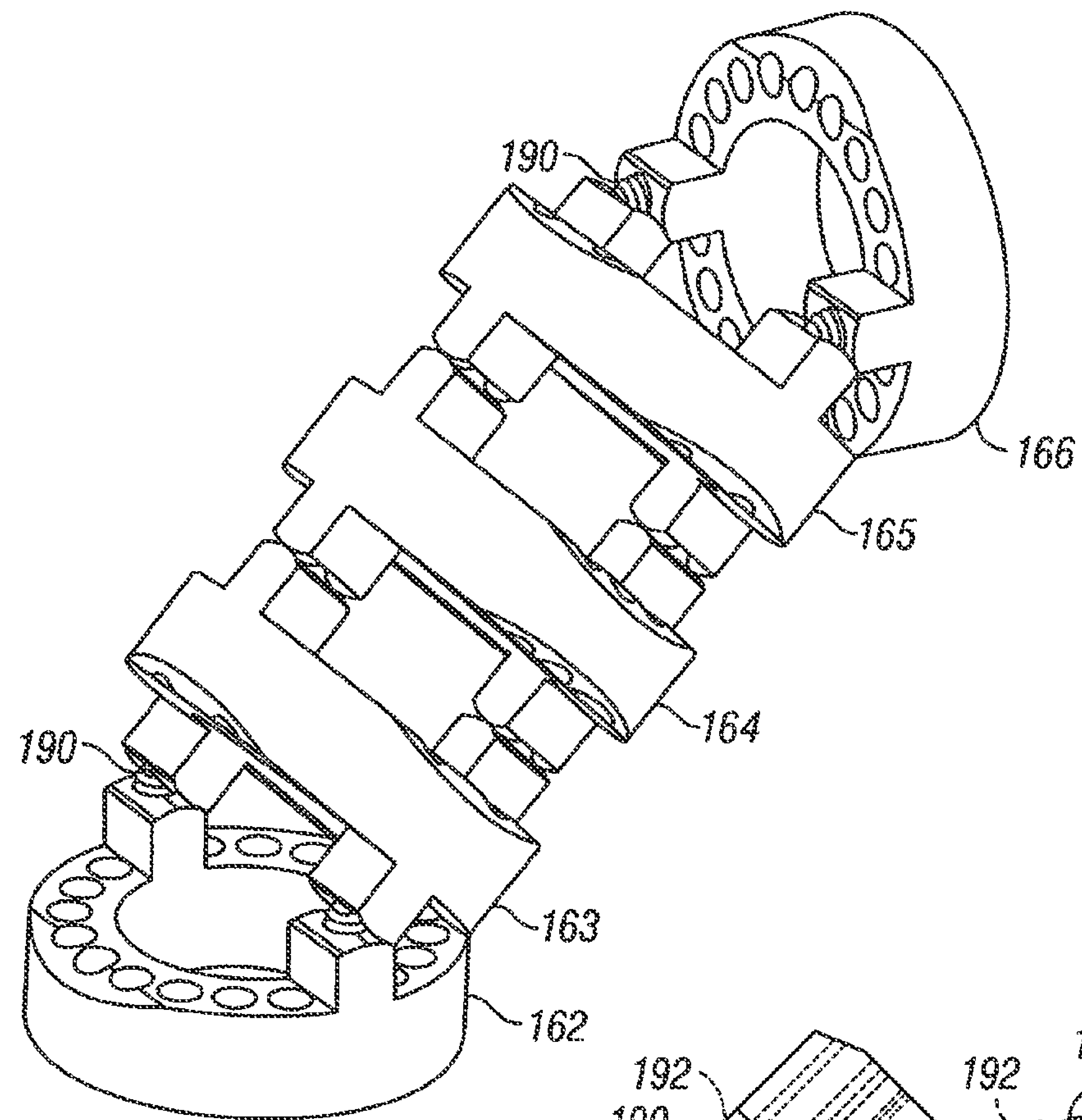

FIG. 18

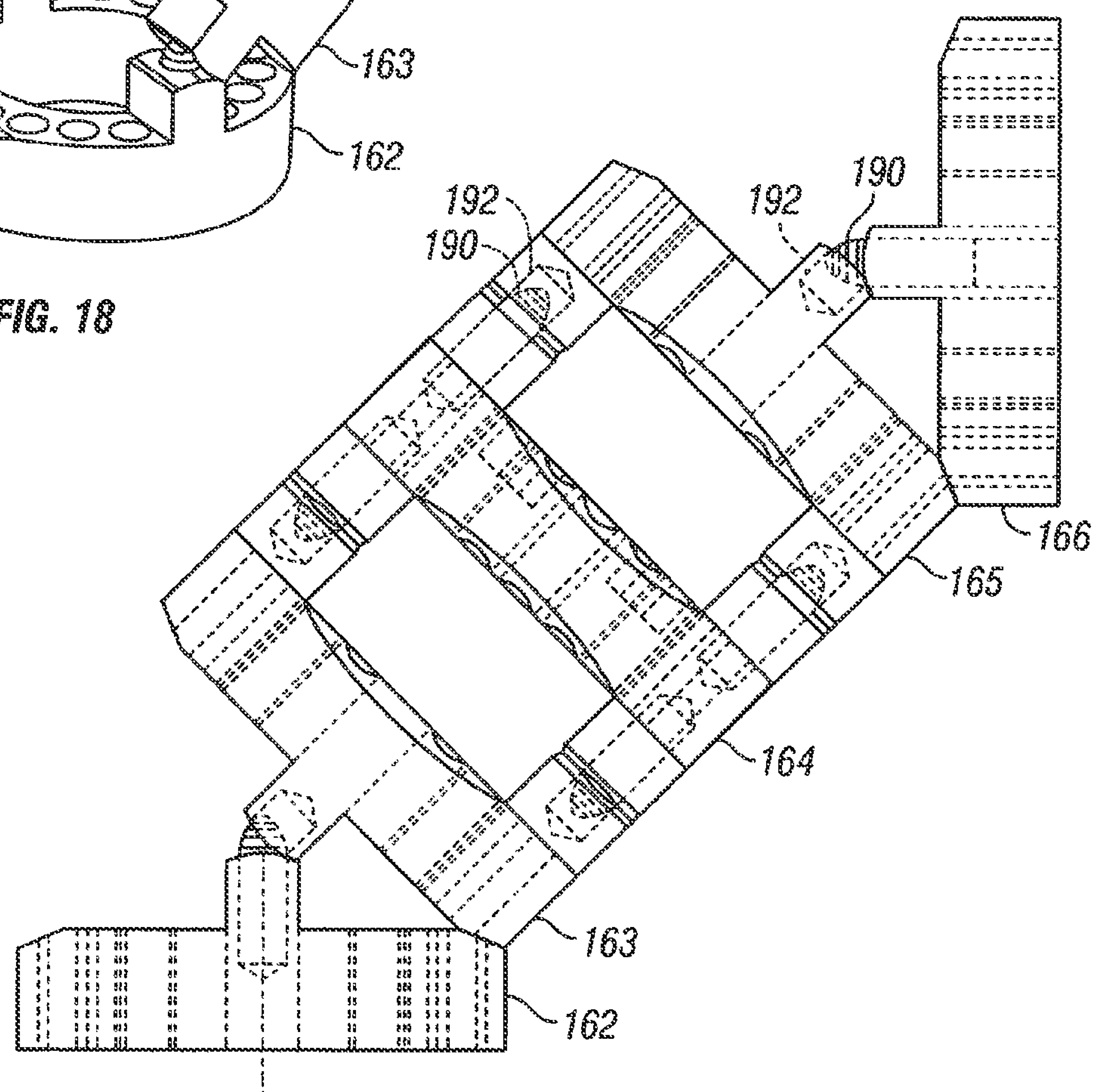

FIG. 19

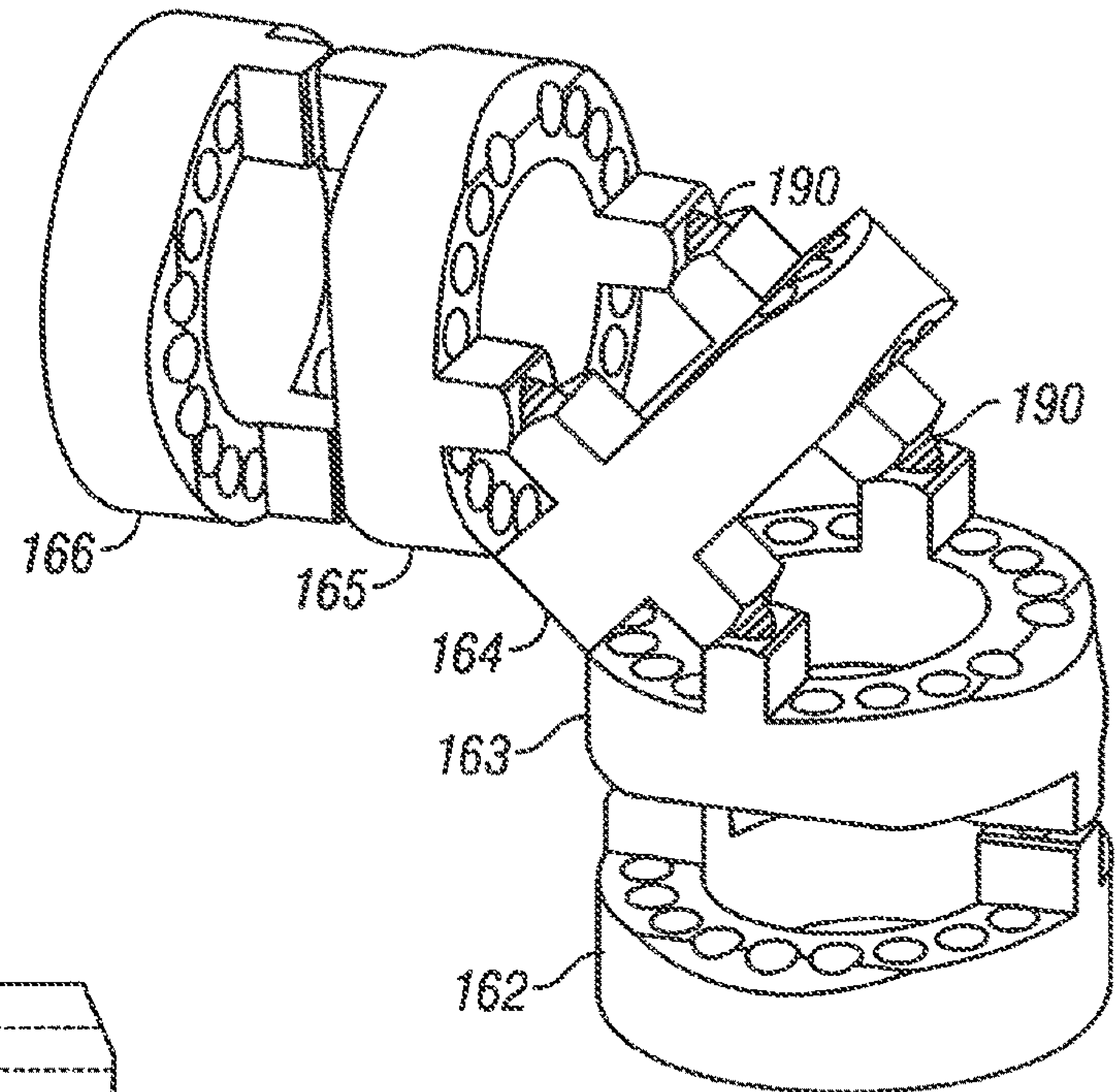

FIG. 20

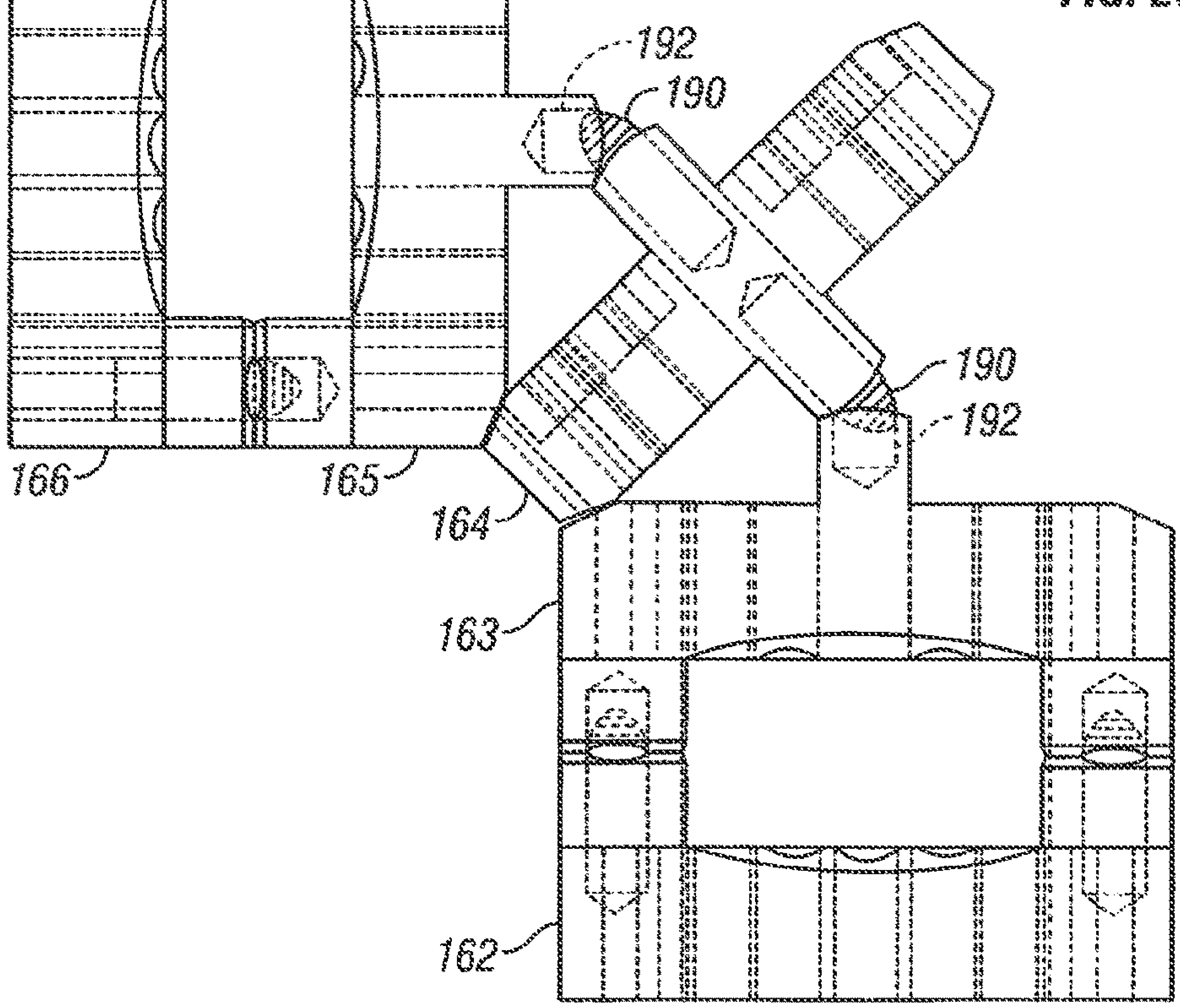

FIG. 21

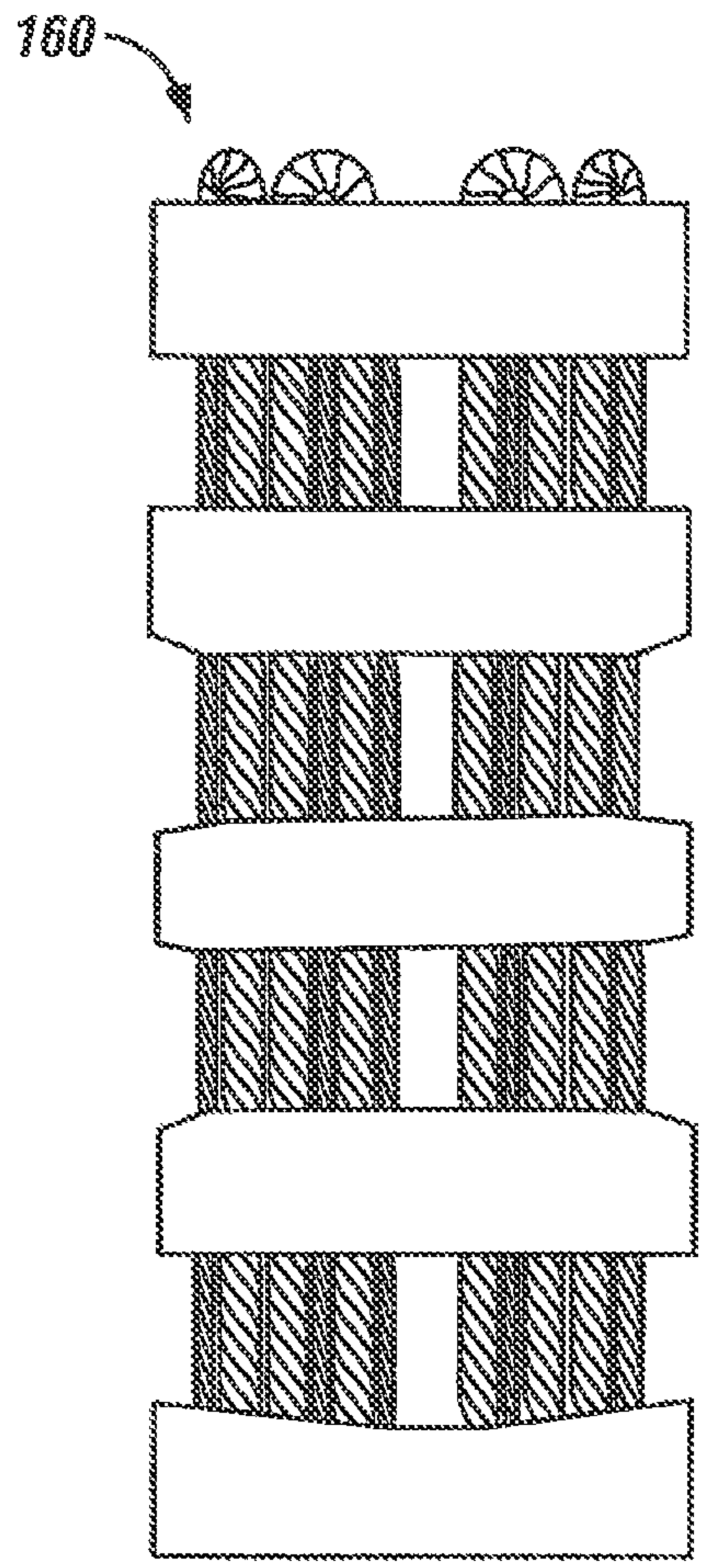

FIG. 22

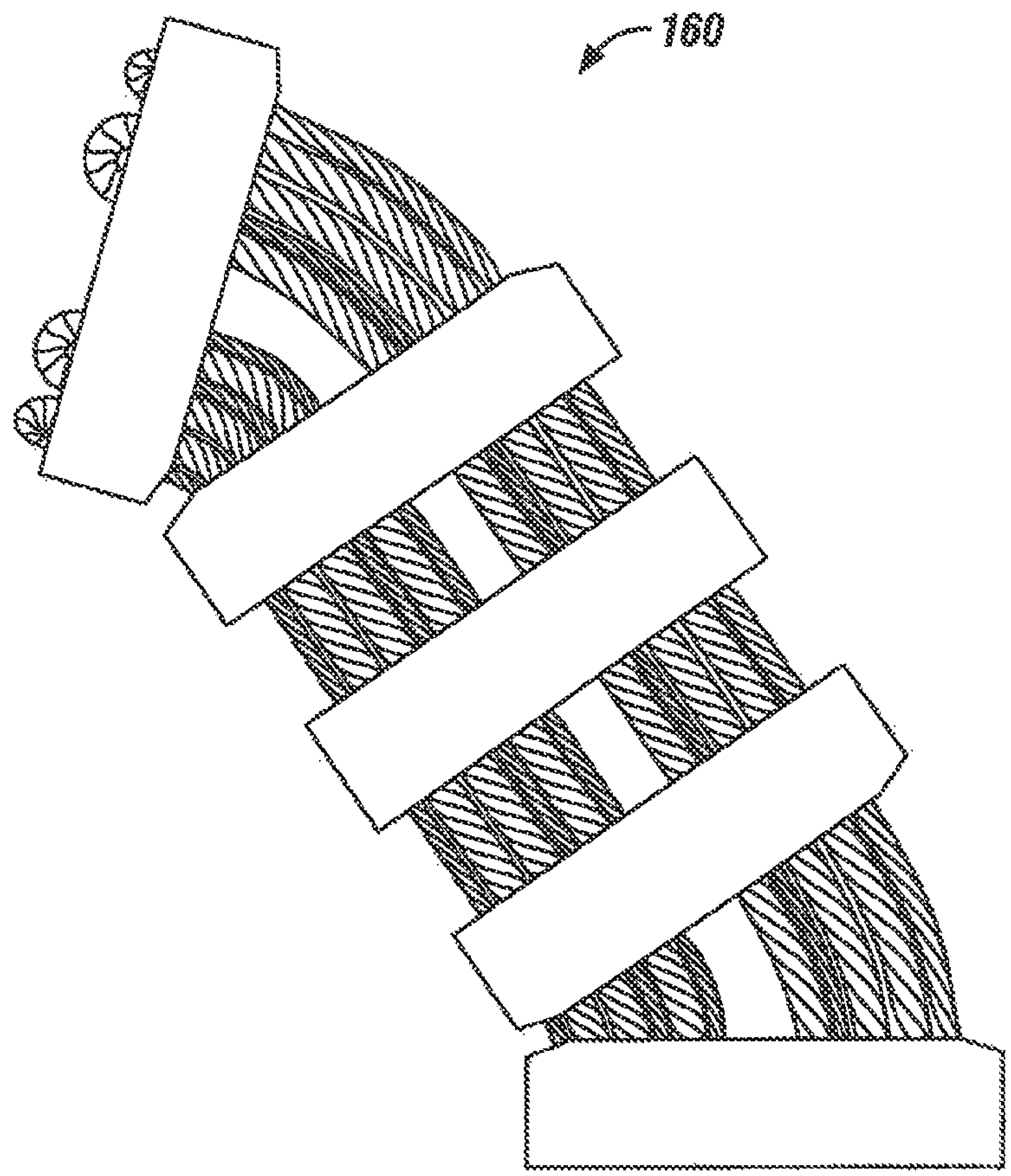

FIG. 23

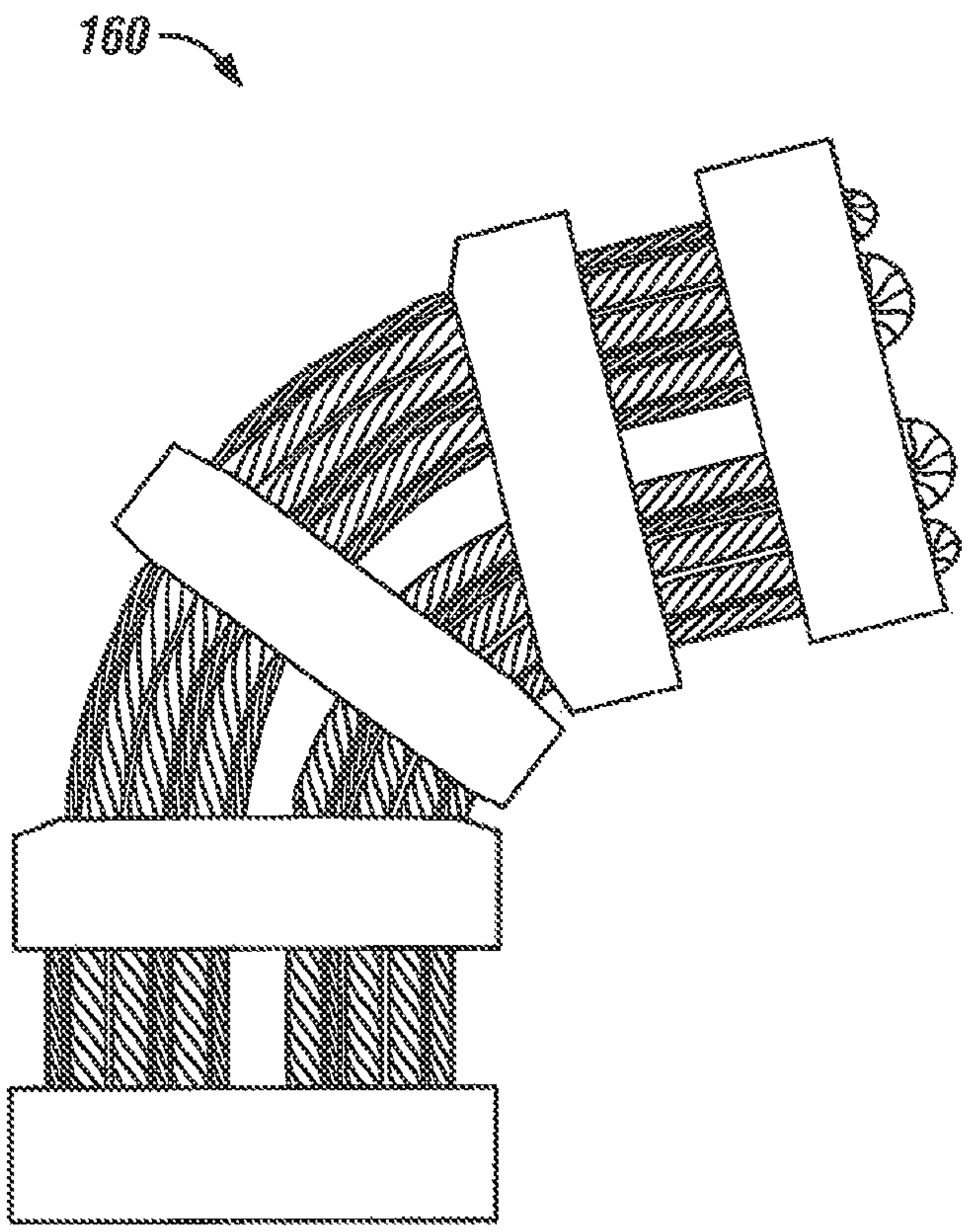

FIG. 24

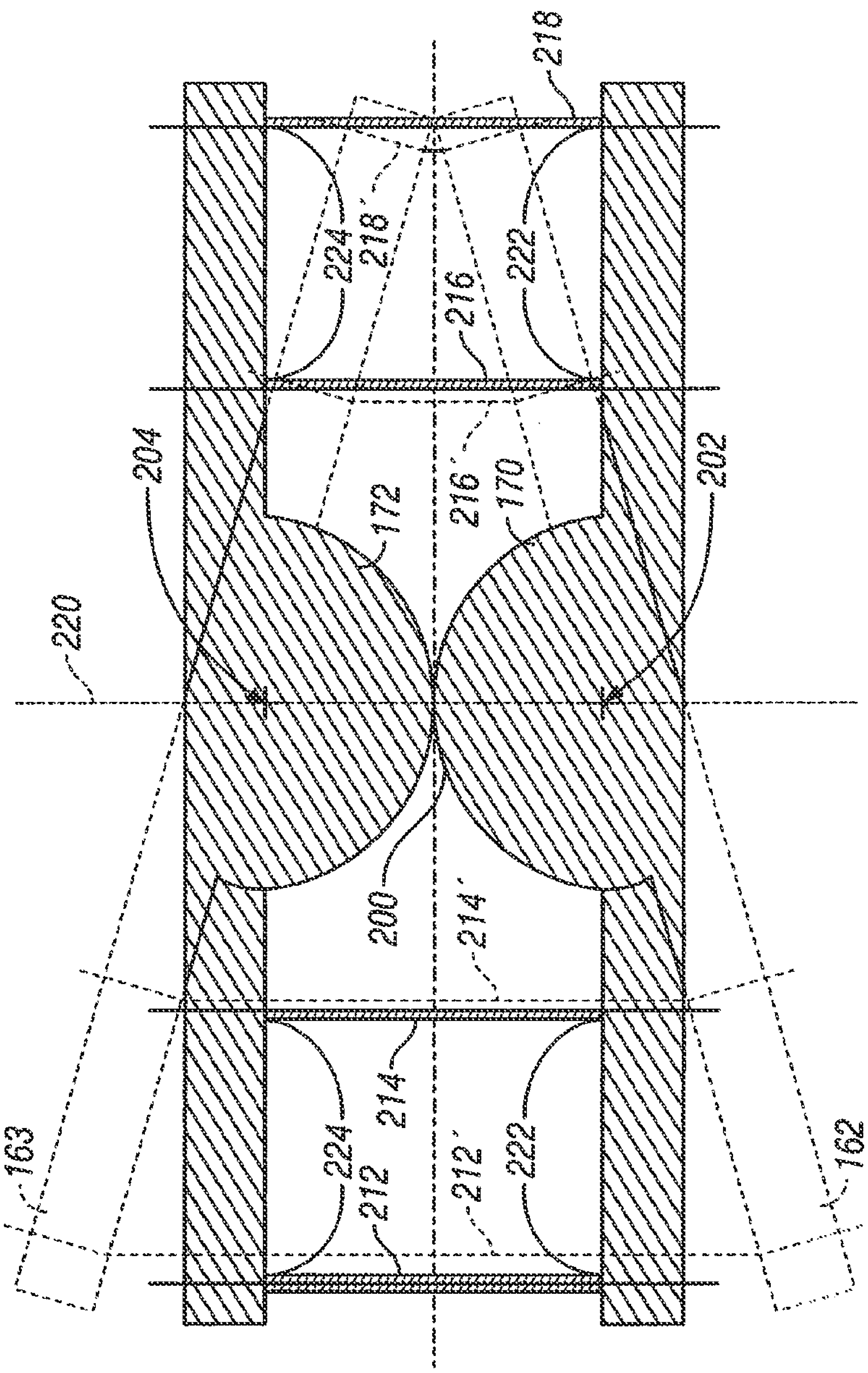
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FIG. 25

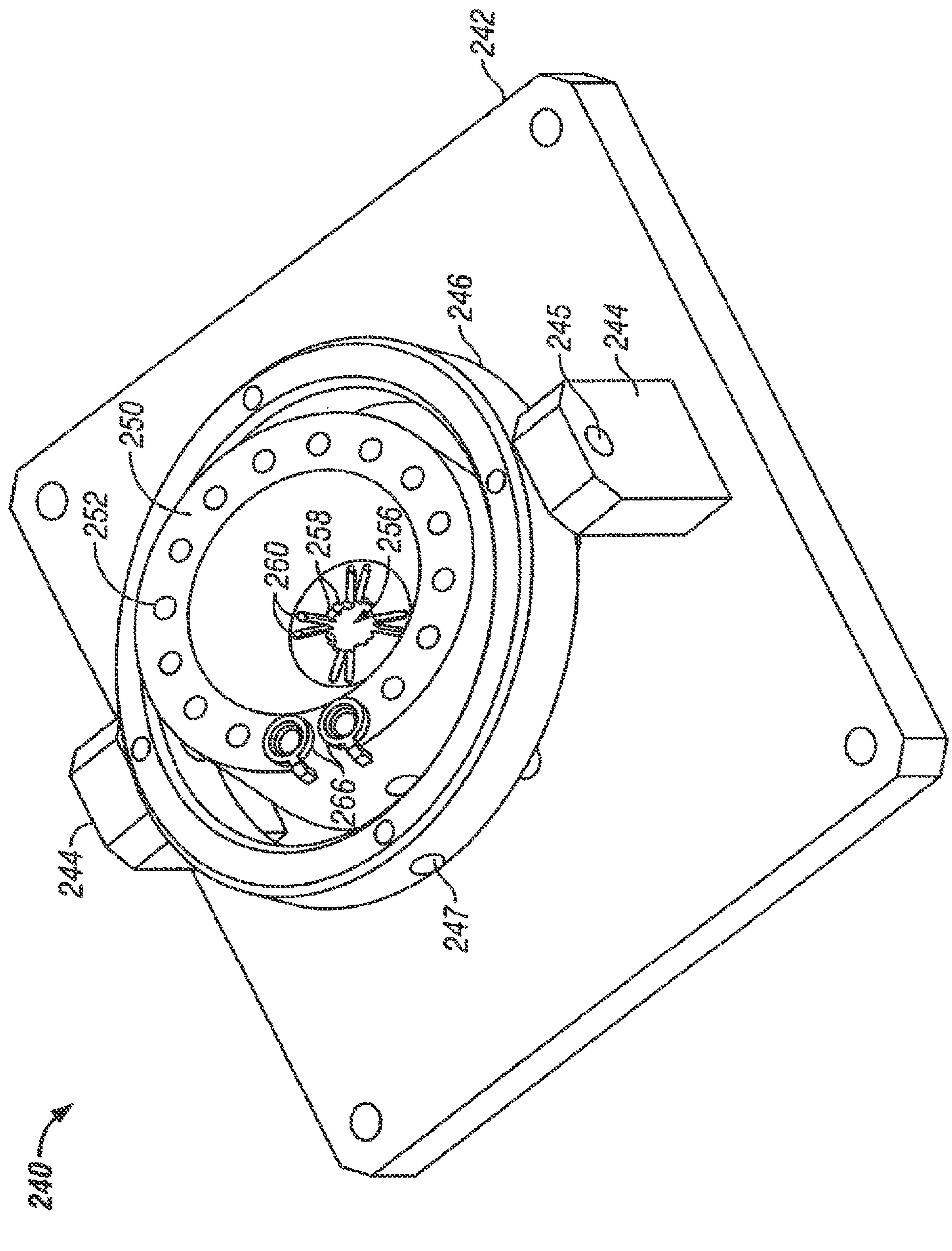

FIG. 26

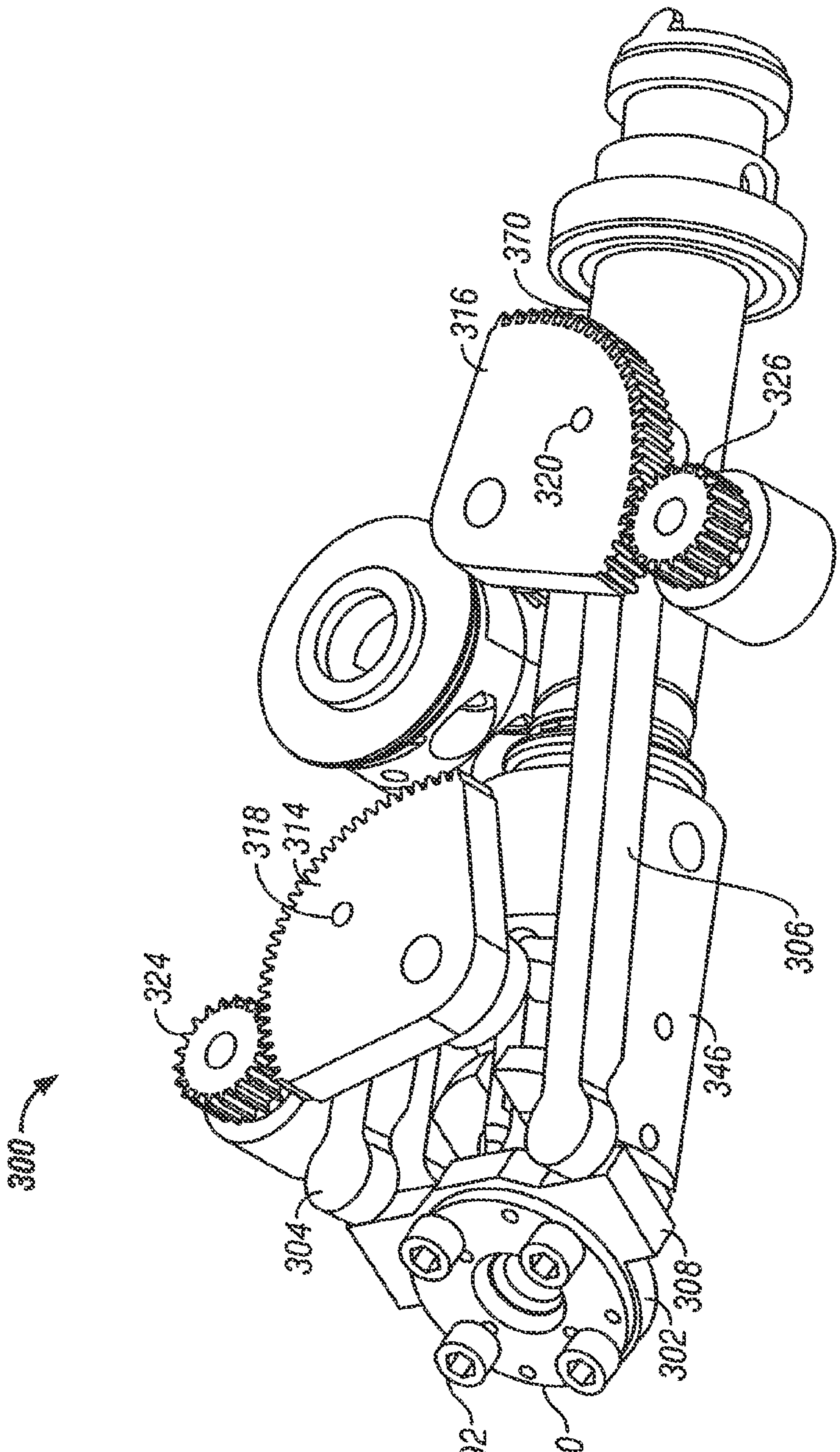

FIG. 27

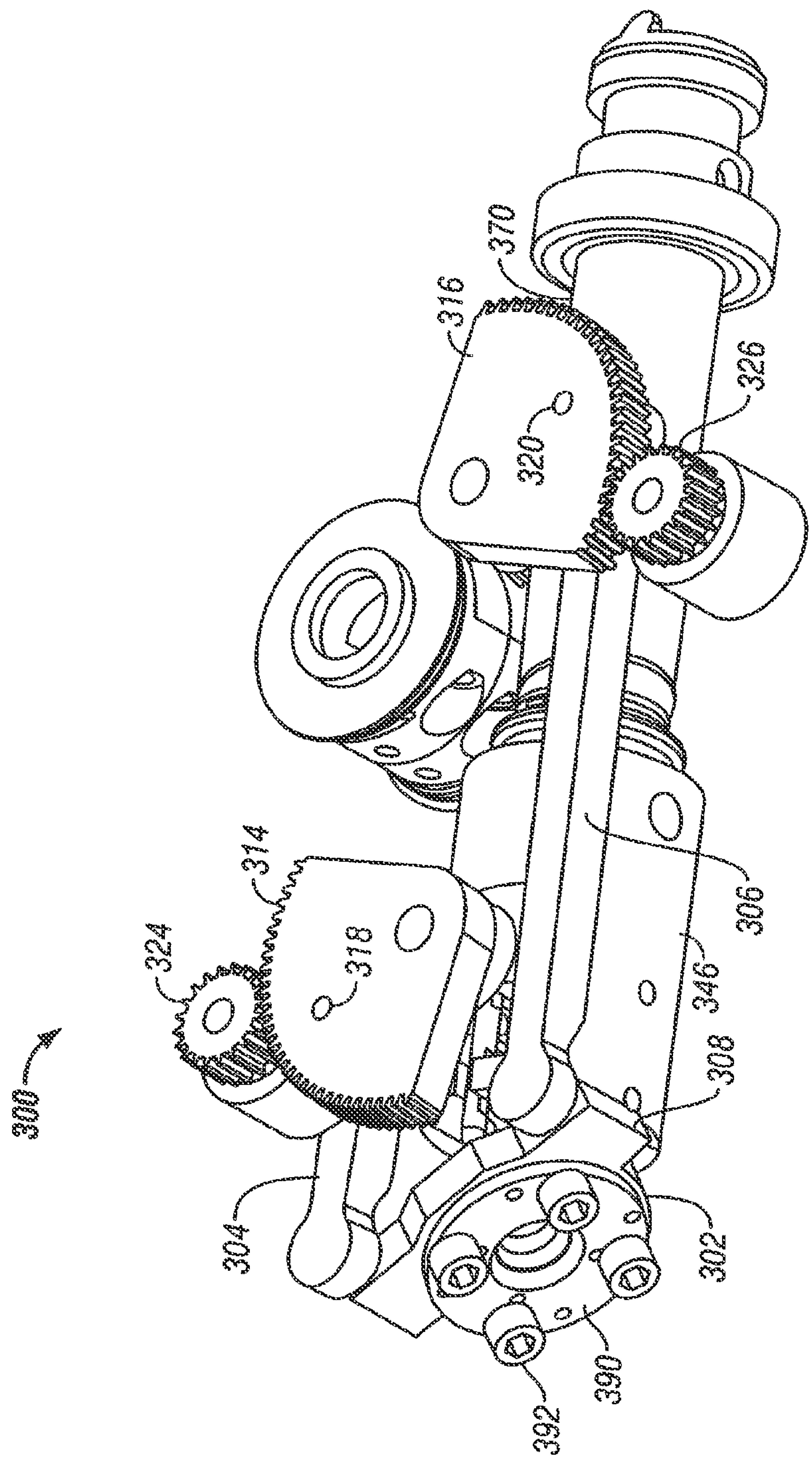

FIG. 28

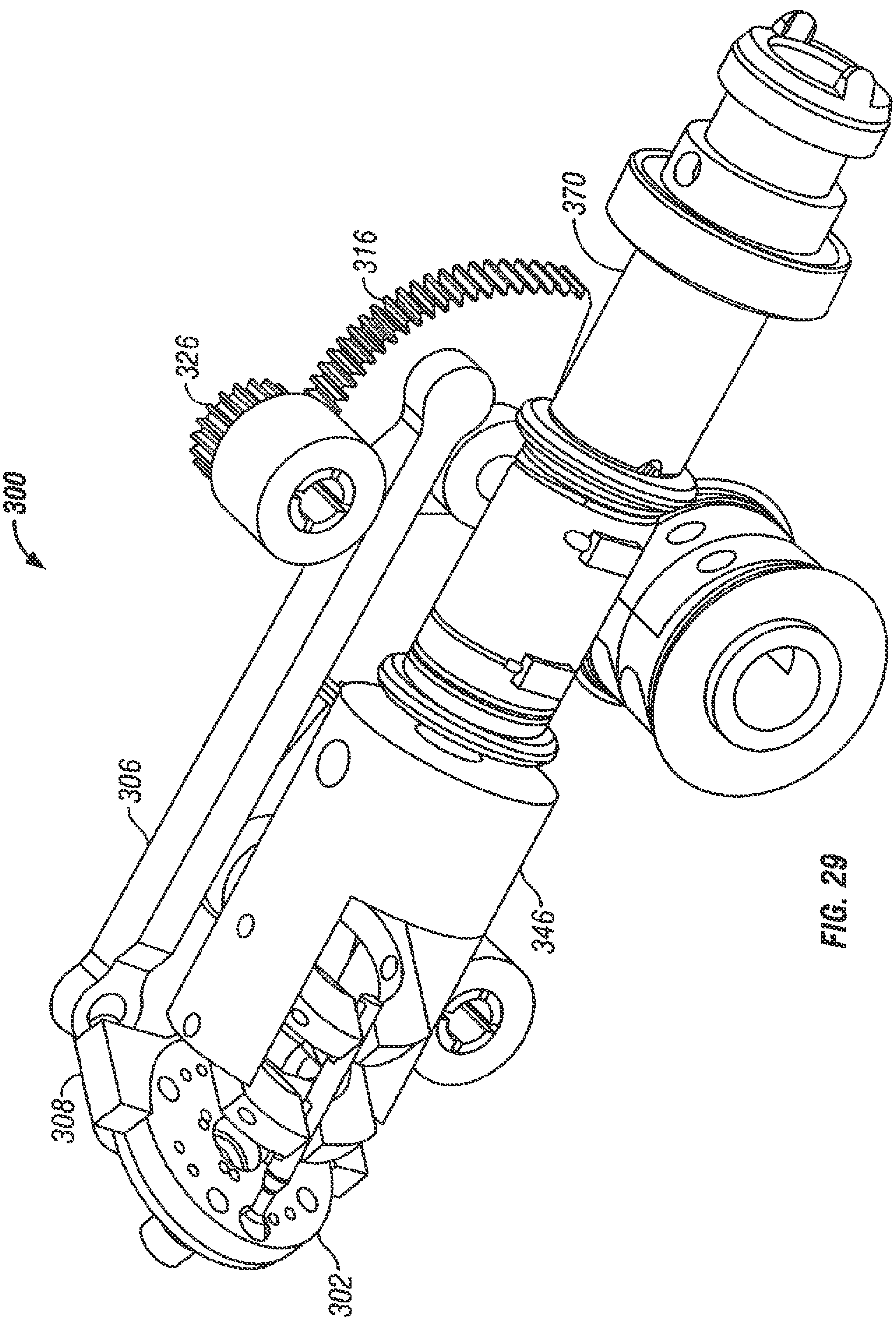

FIG. 29

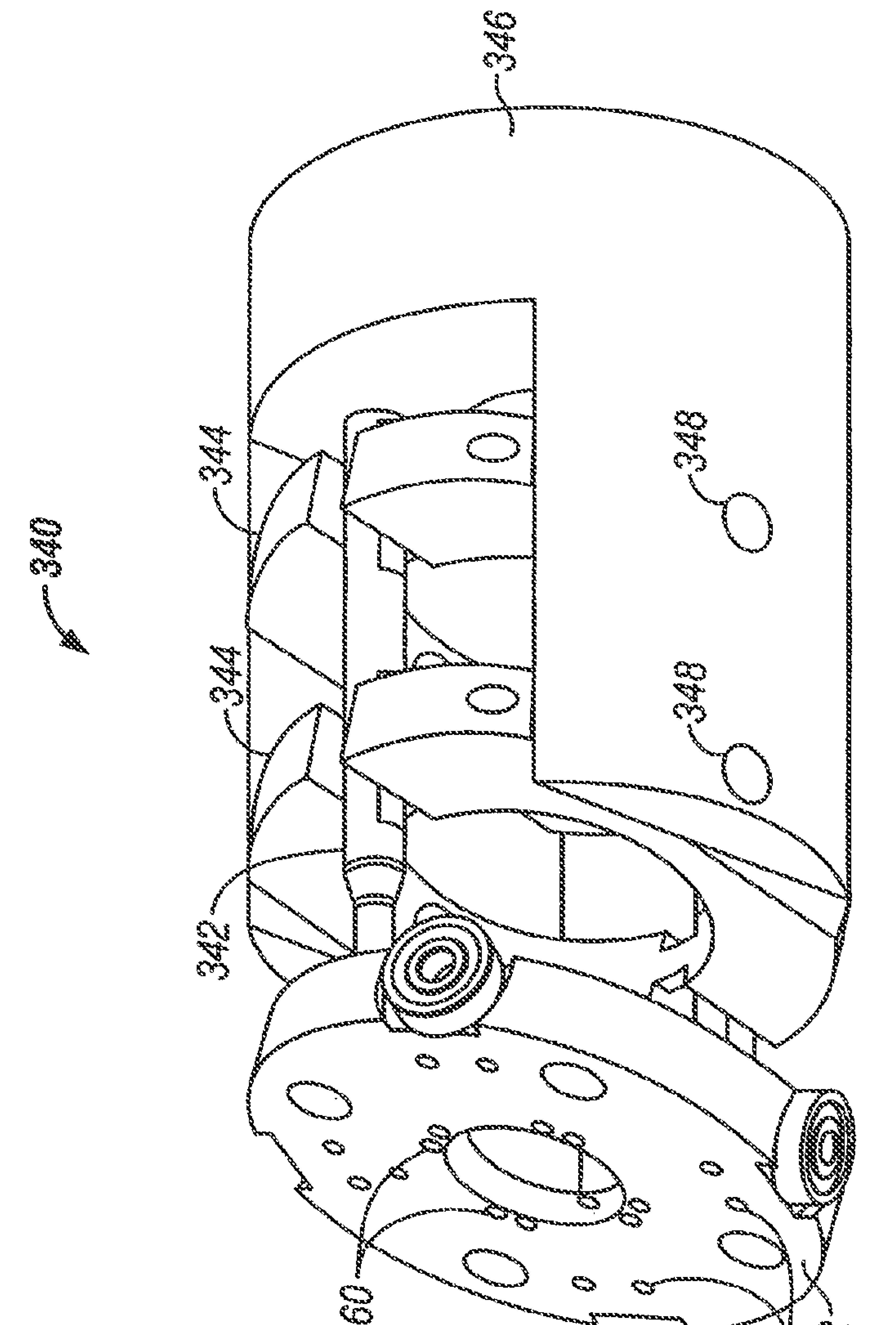

FIG. 30

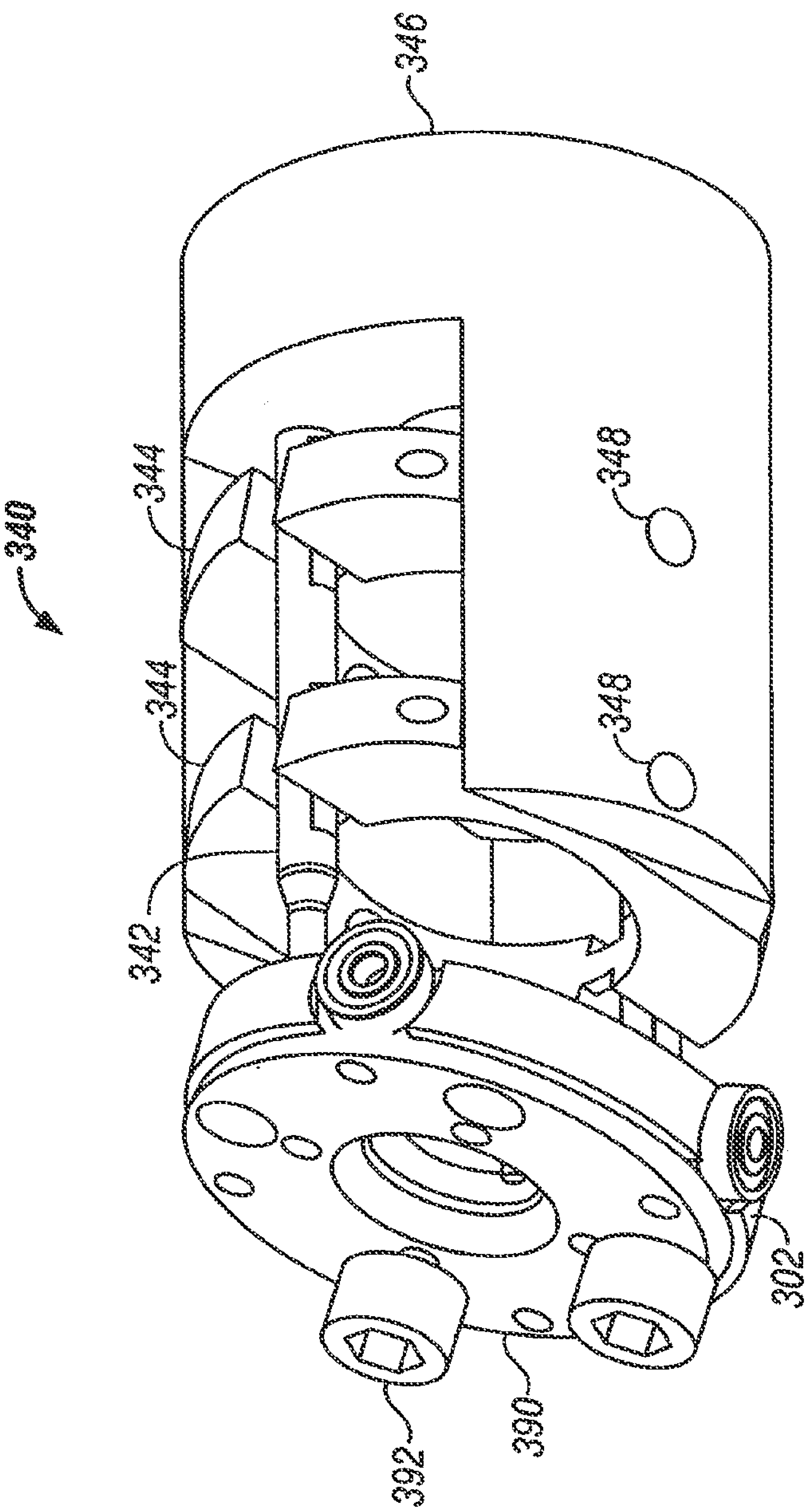

FIG. 31

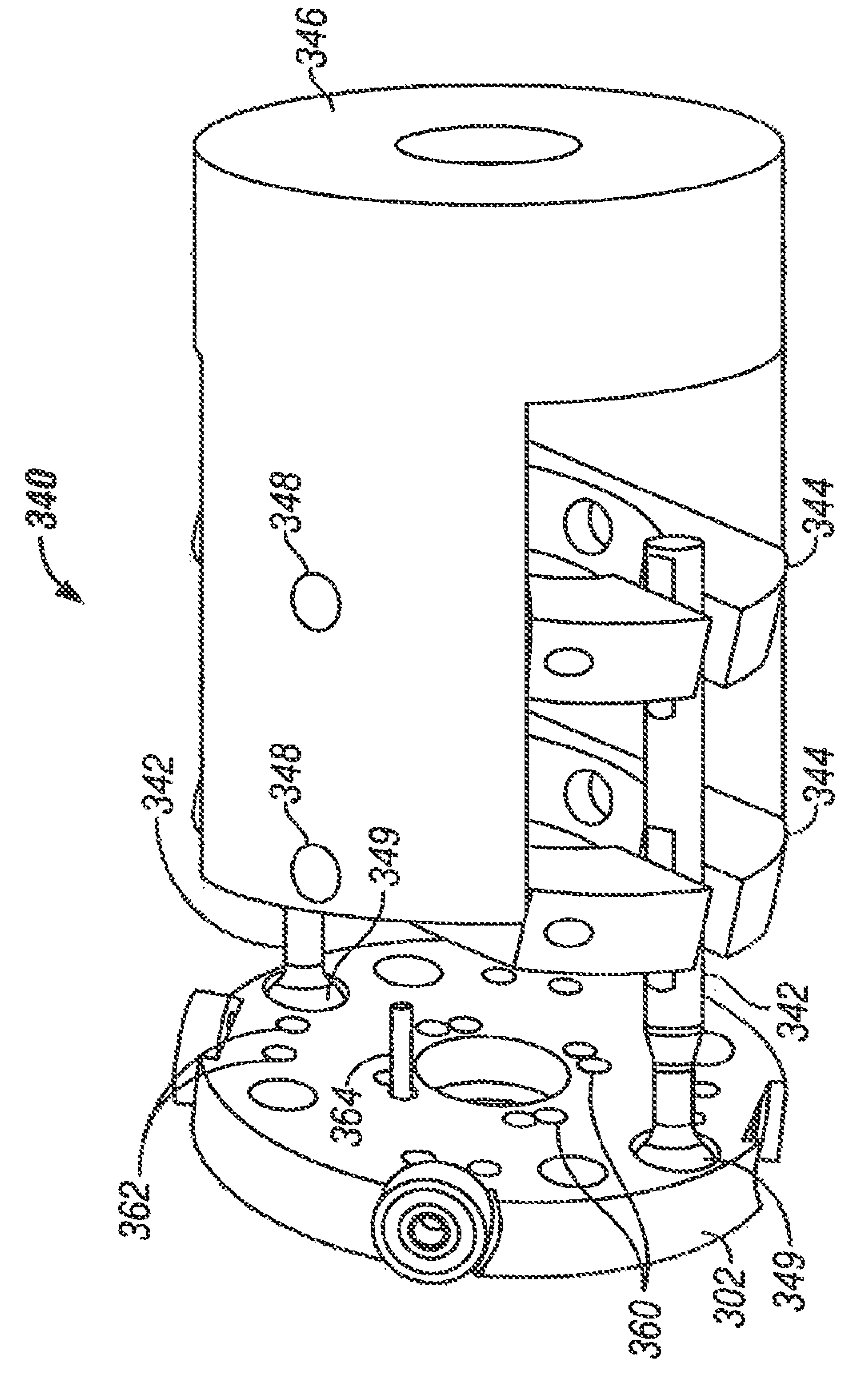

FIG. 32

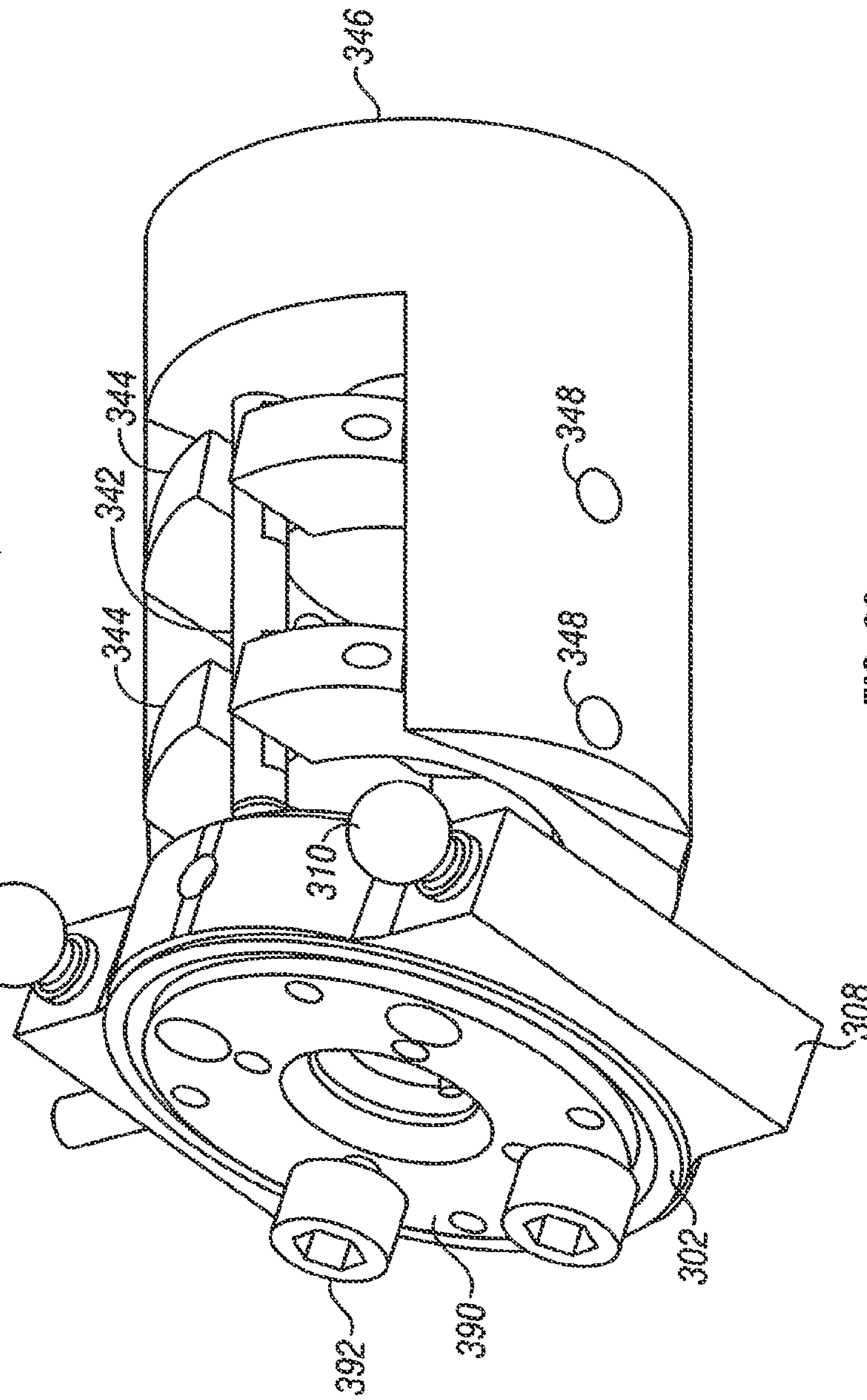

FIG. 33

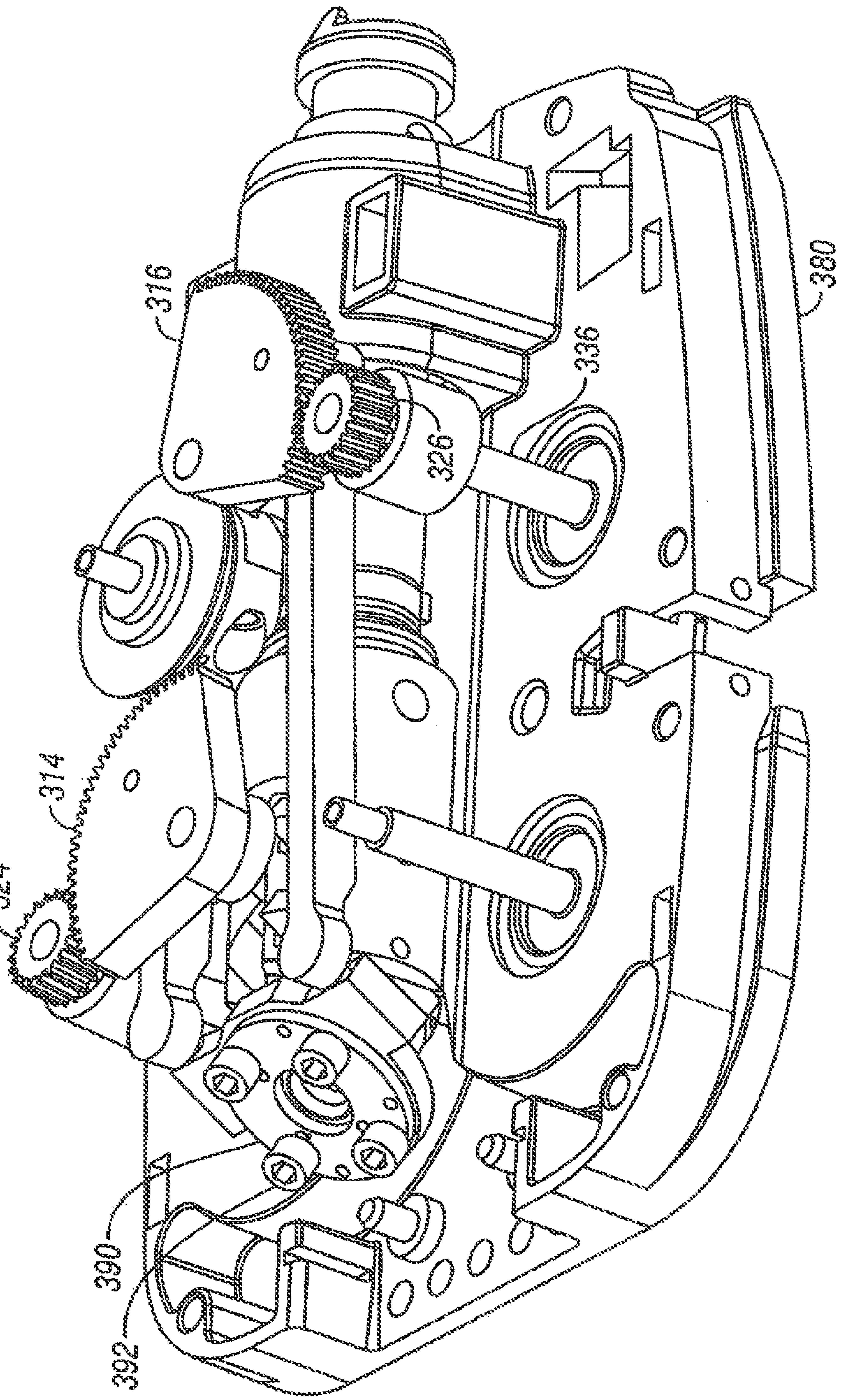

FIG. 34

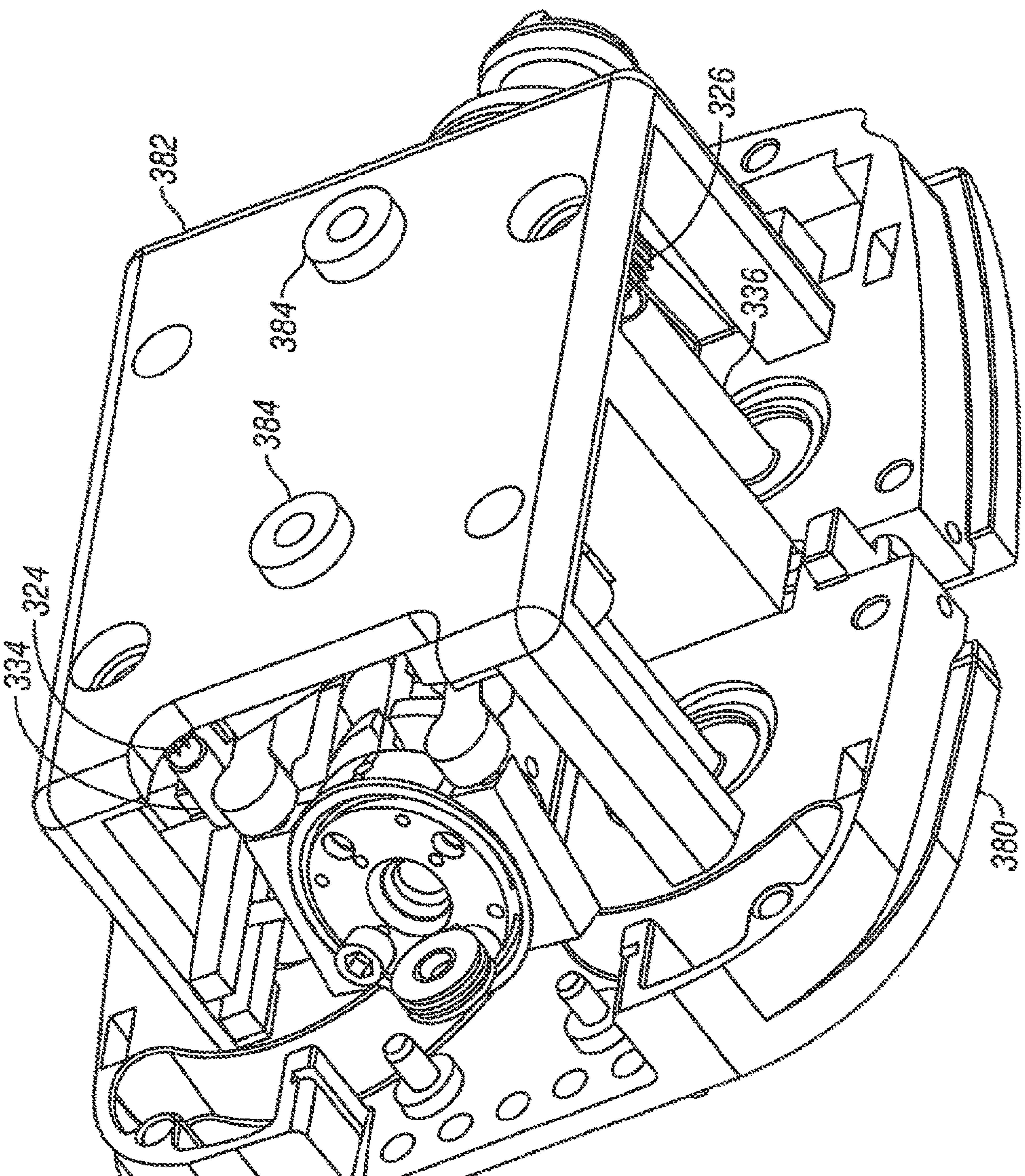

FIG. 35

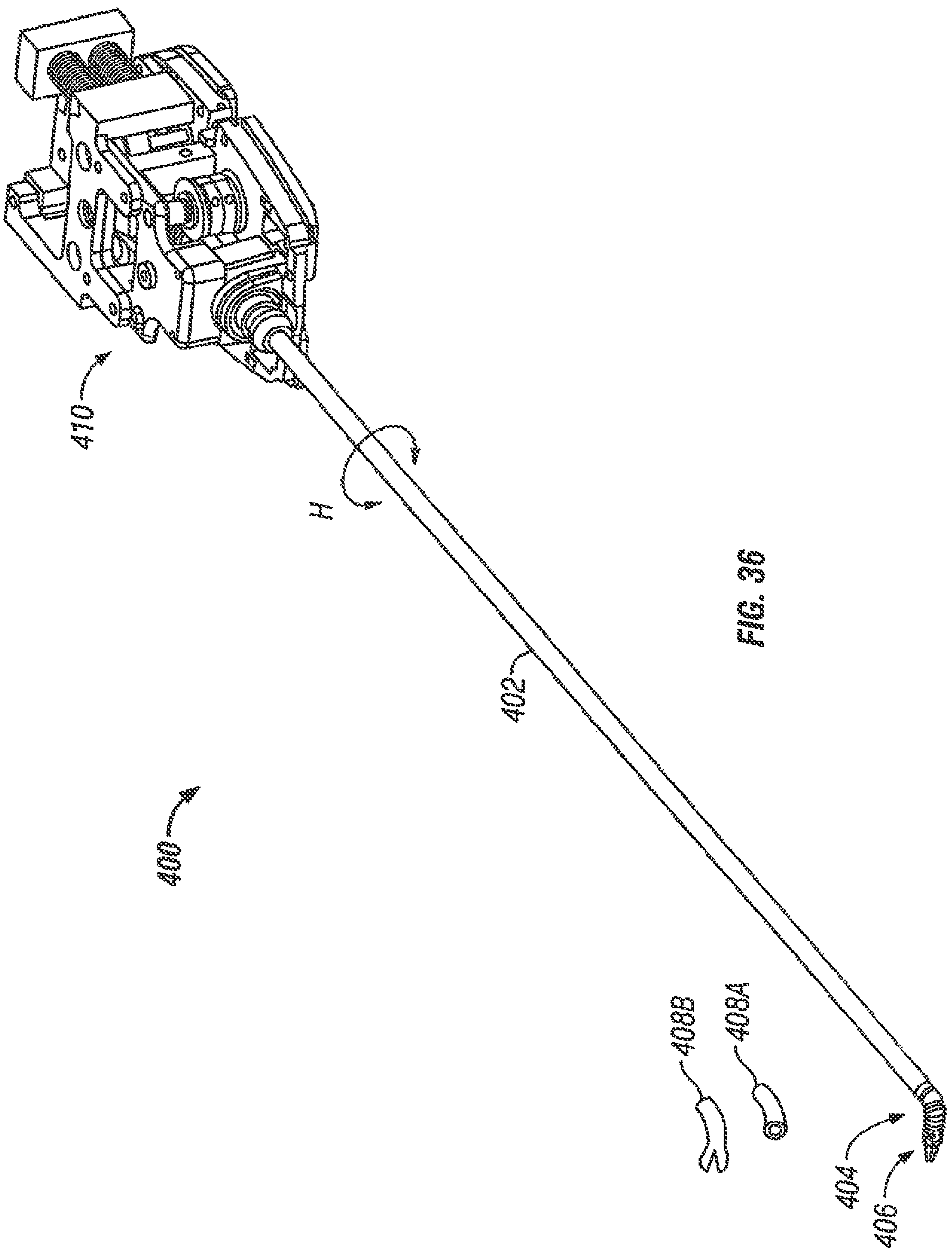

FIG. 36

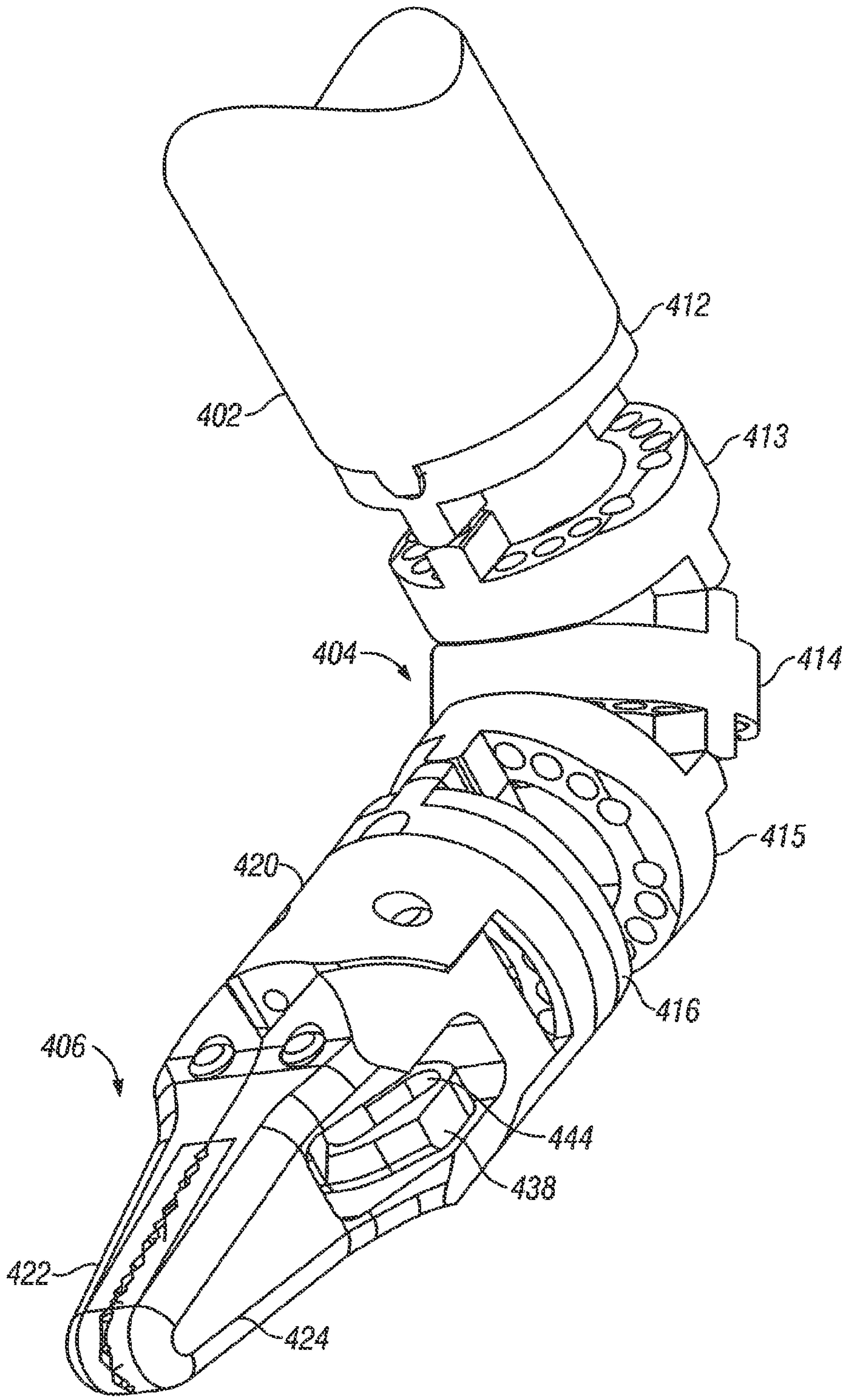

FIG. 37

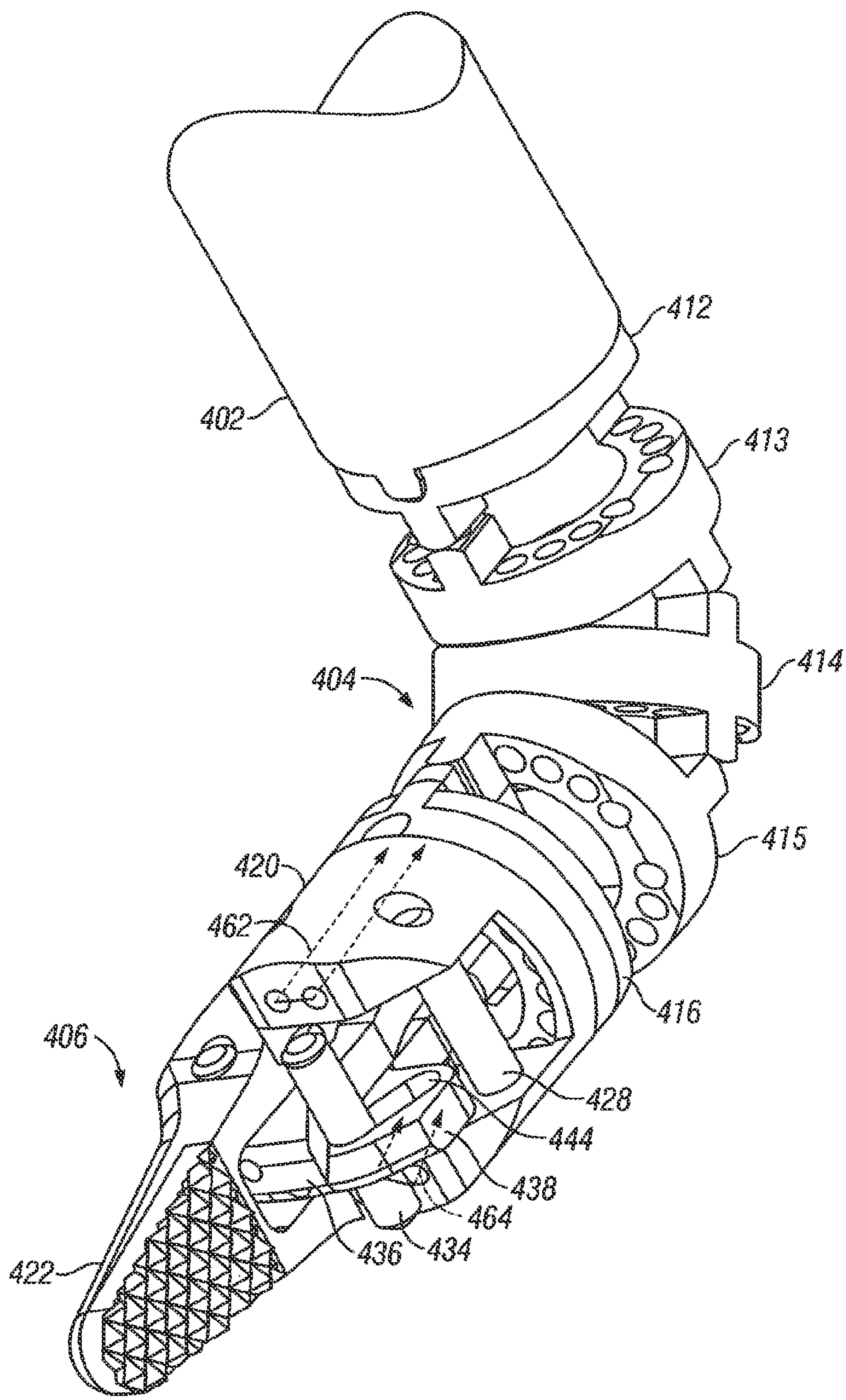
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FIG. 38

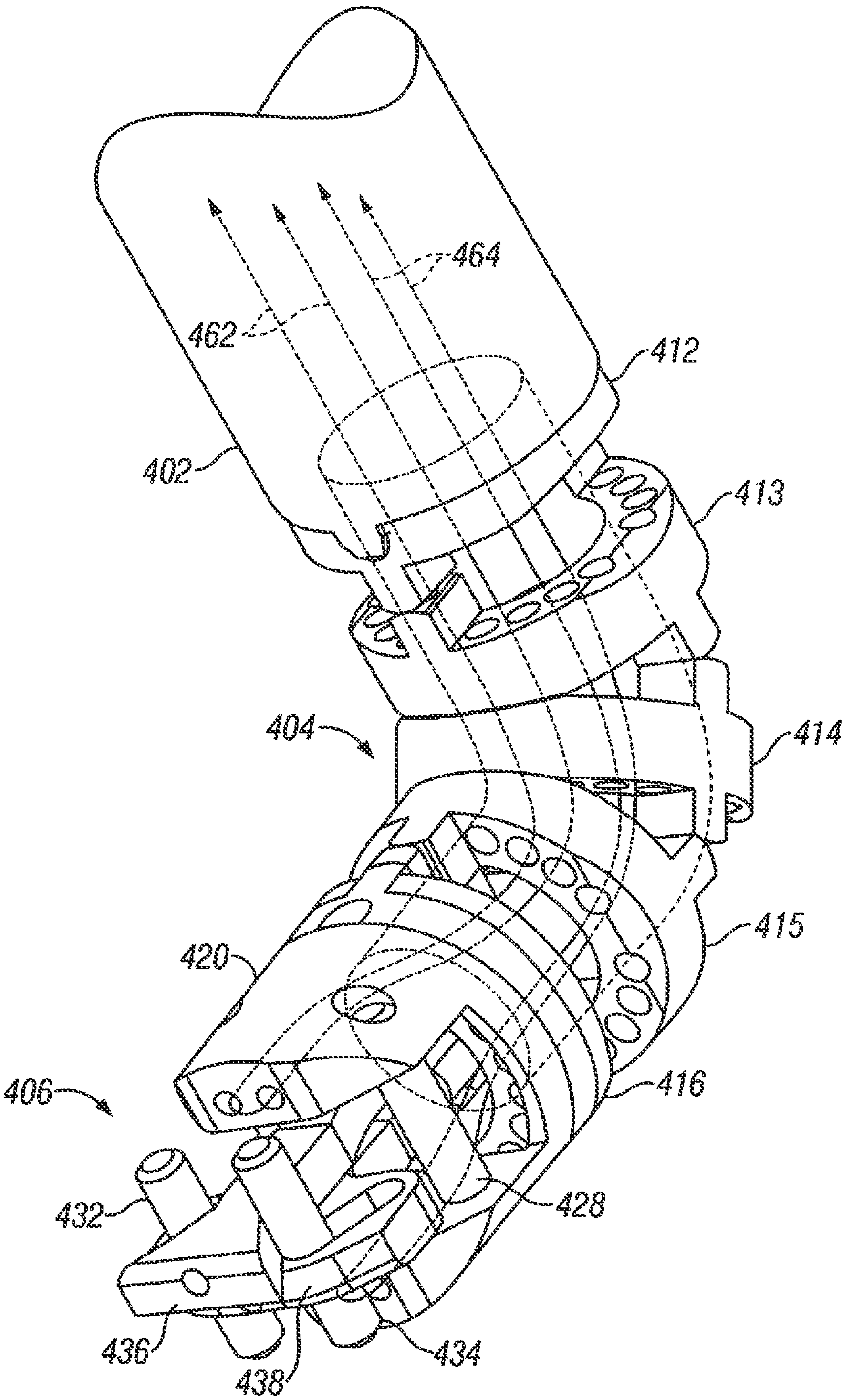

FIG. 38A

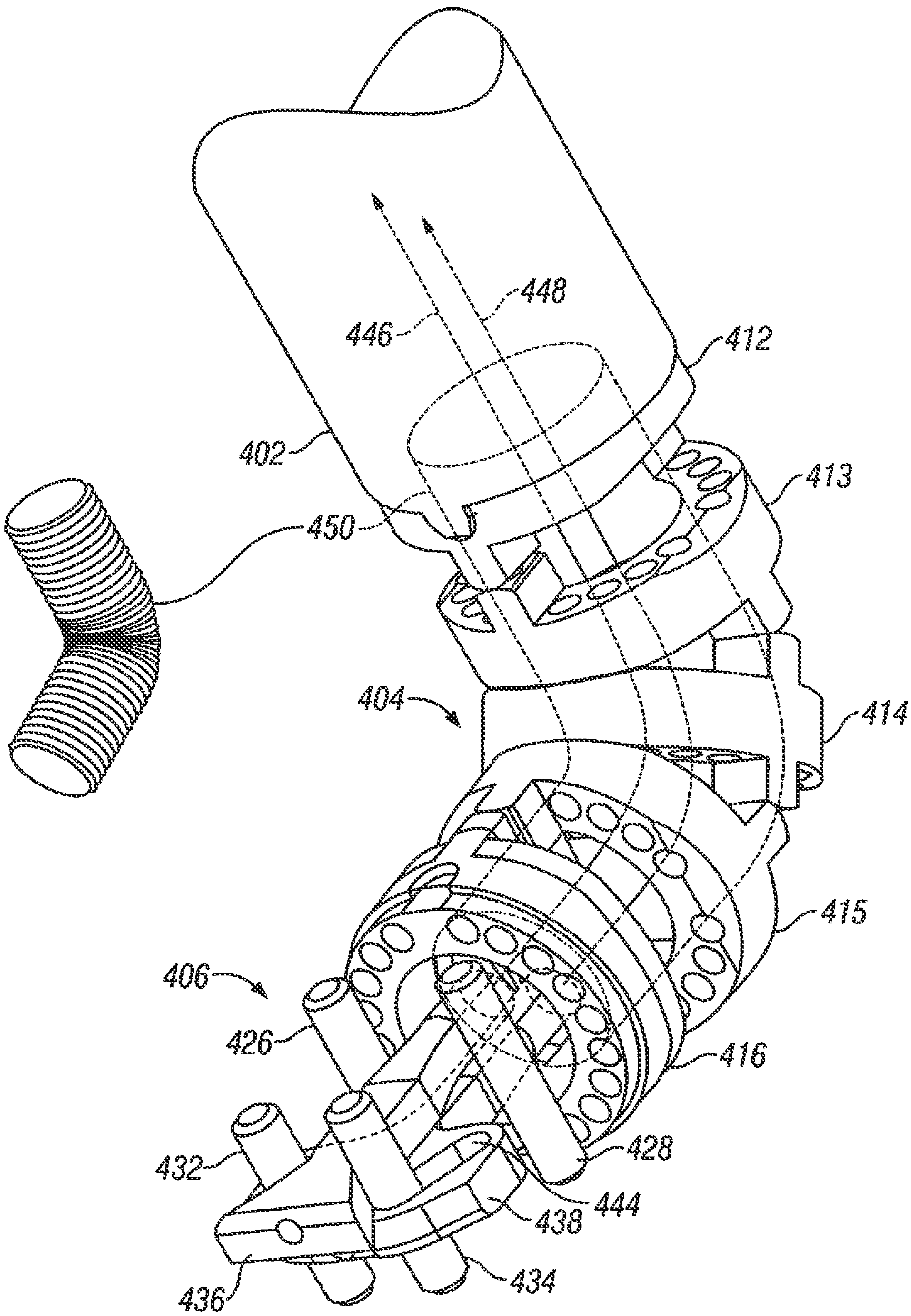
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FIG. 39

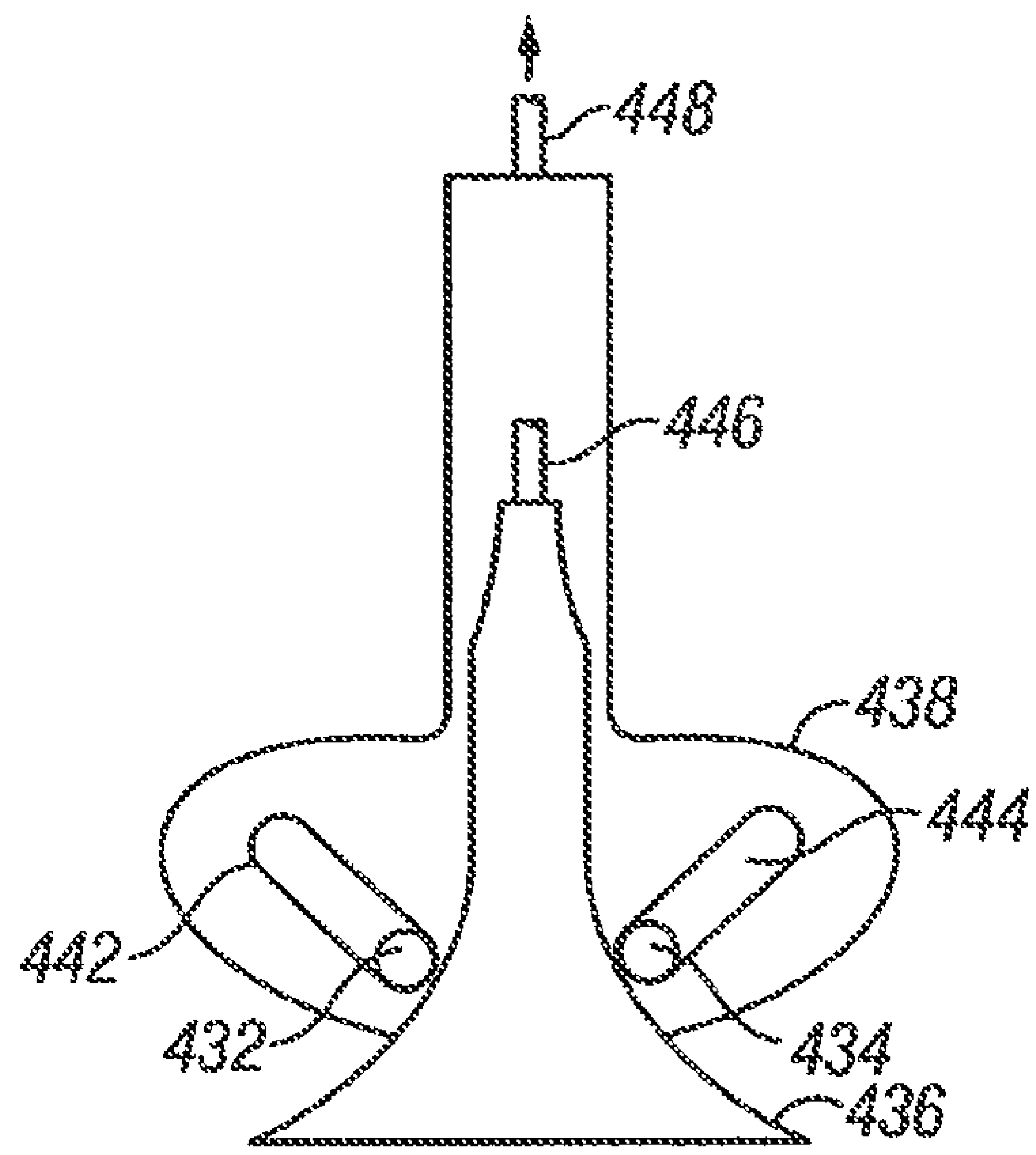

FIG. 39A

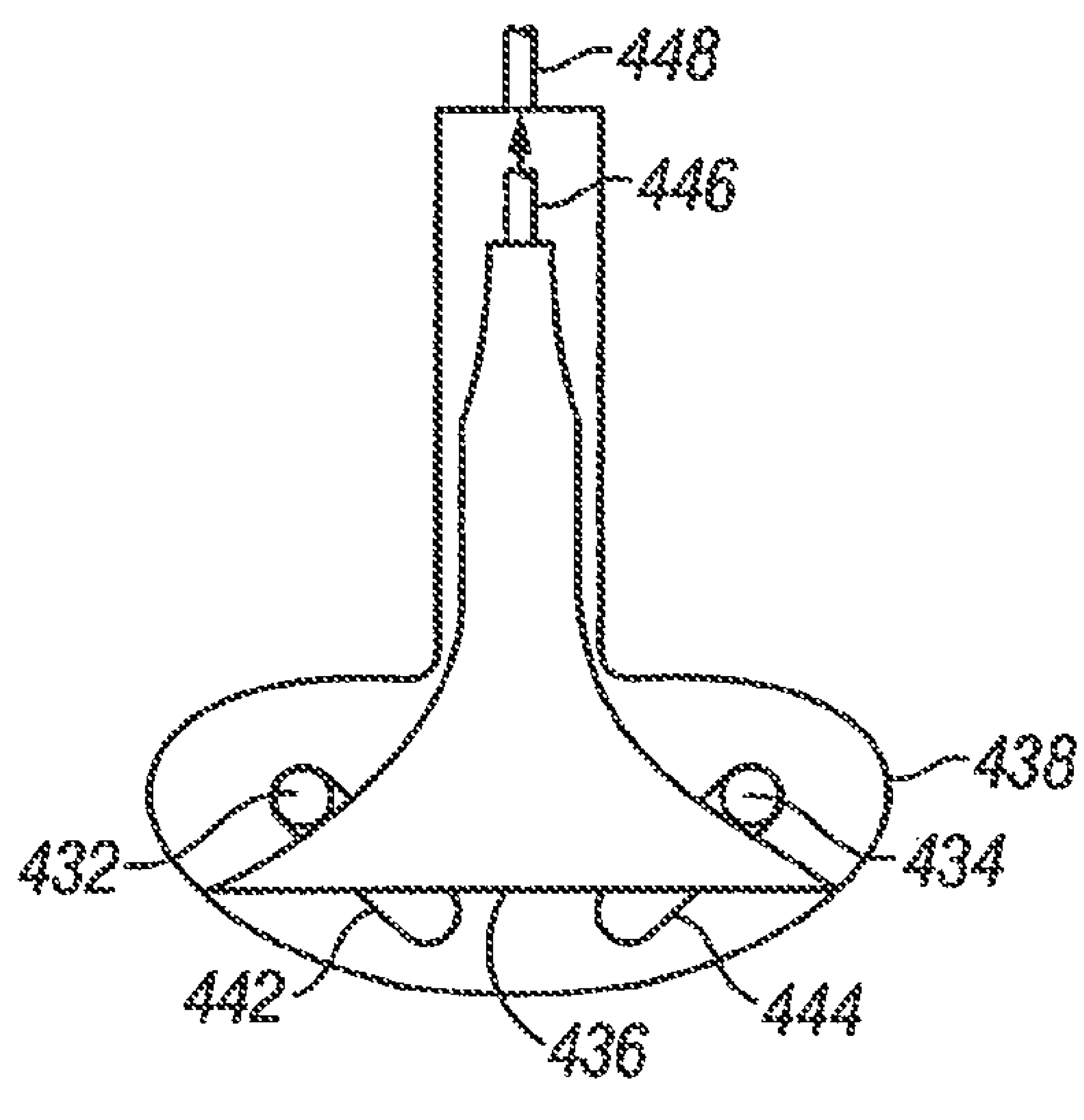

FIG. 39B

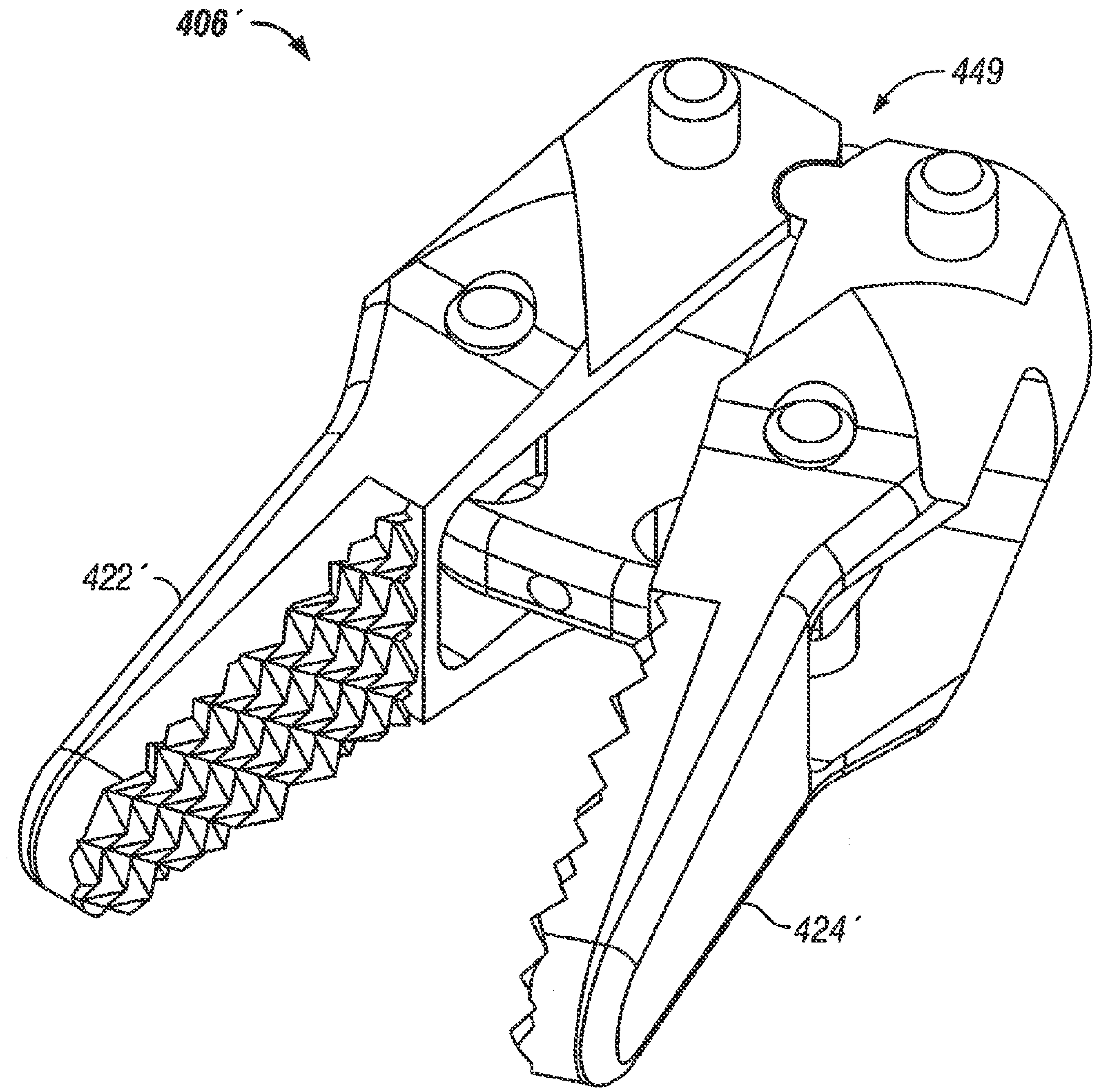

FIG. 39C

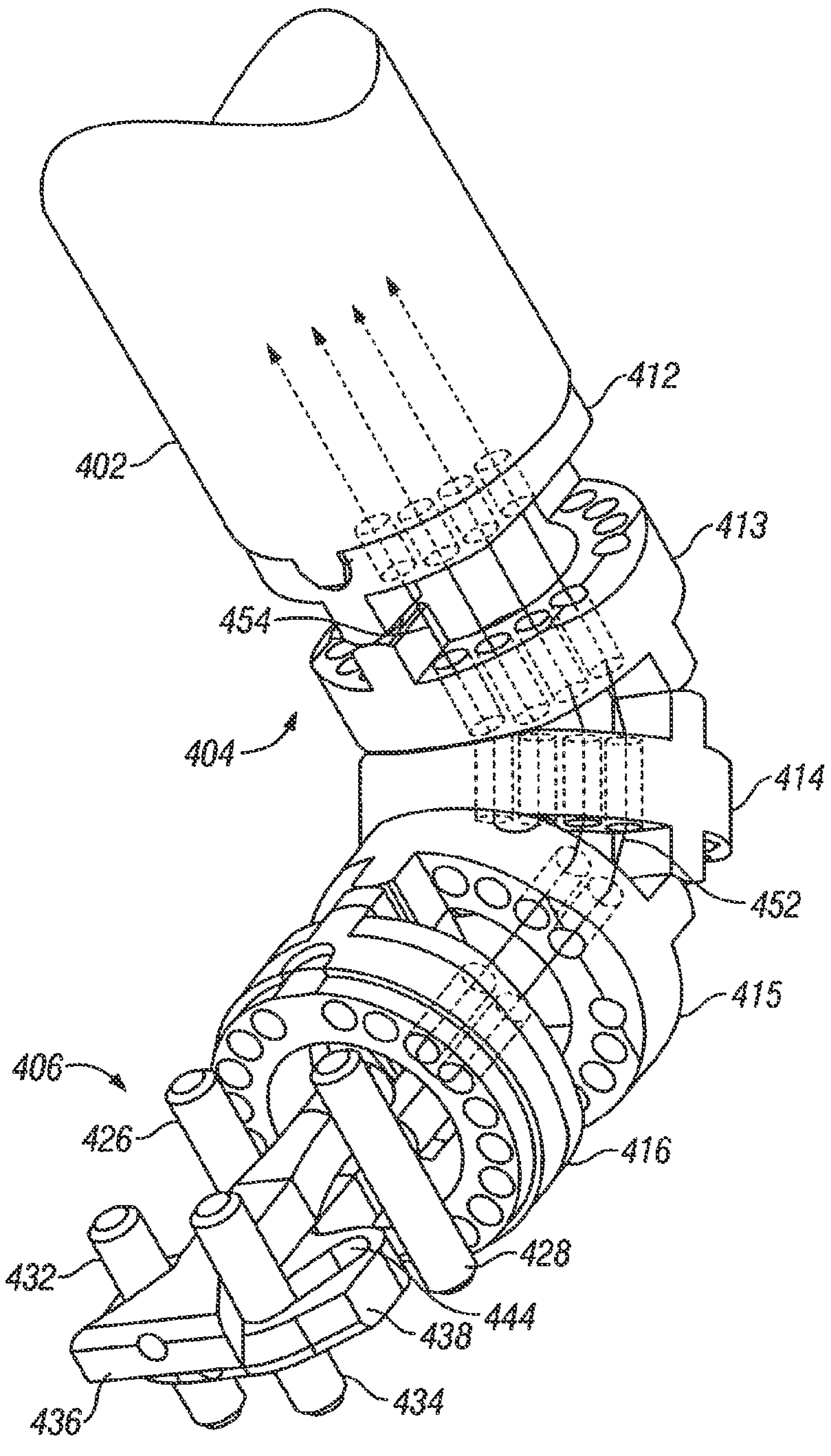
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FIG. 40

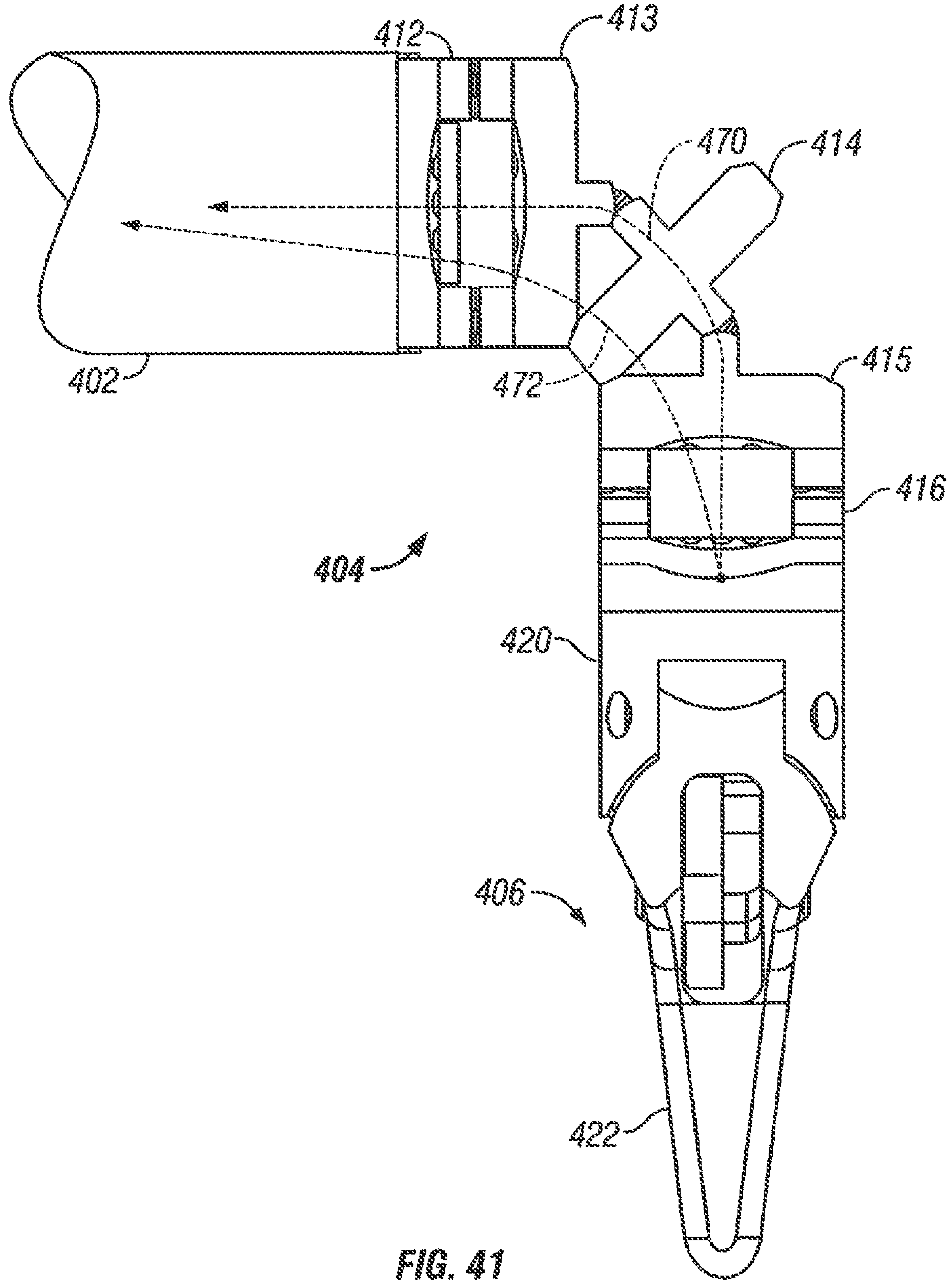

FIG. 41

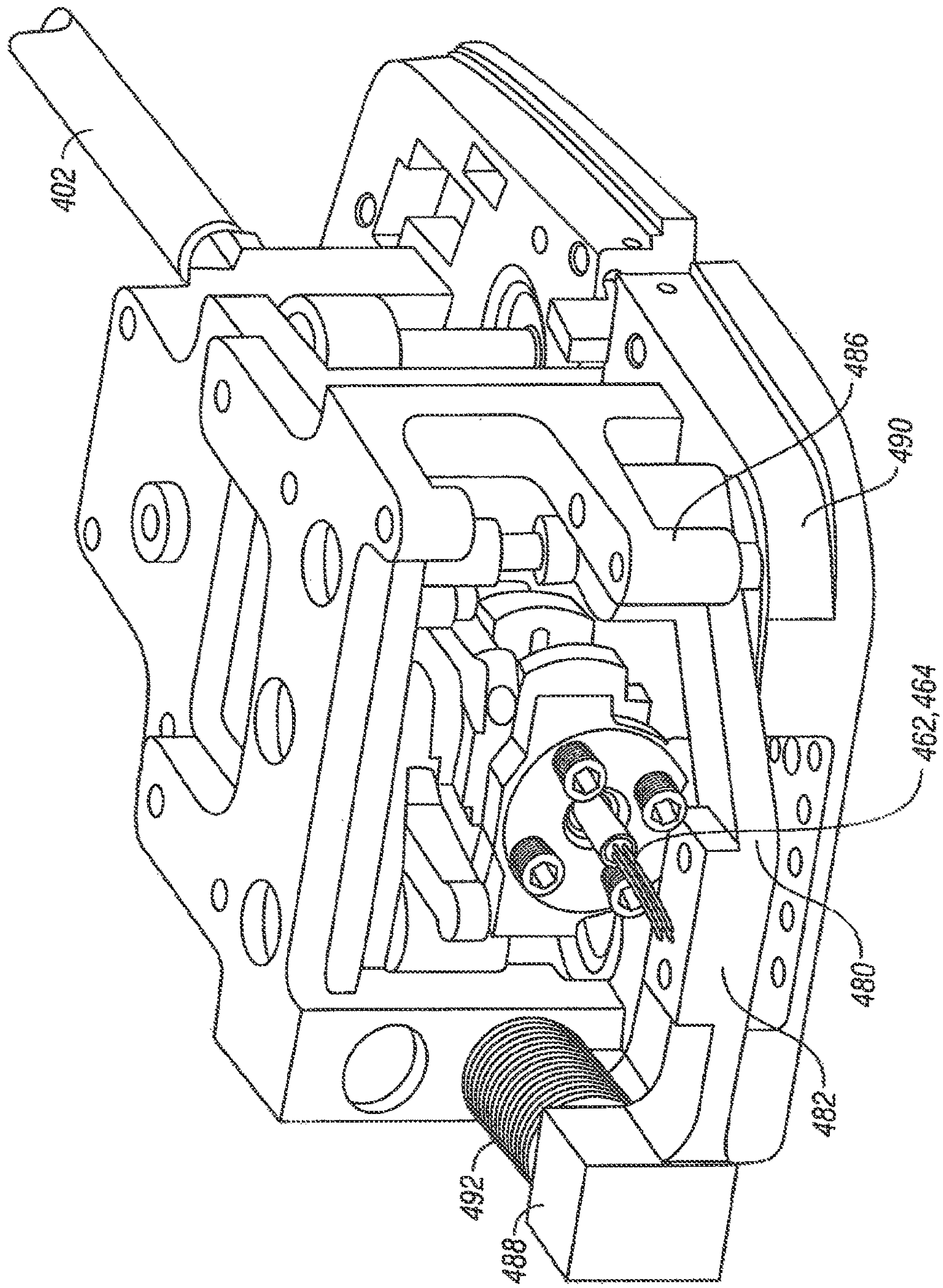

FIG. 42

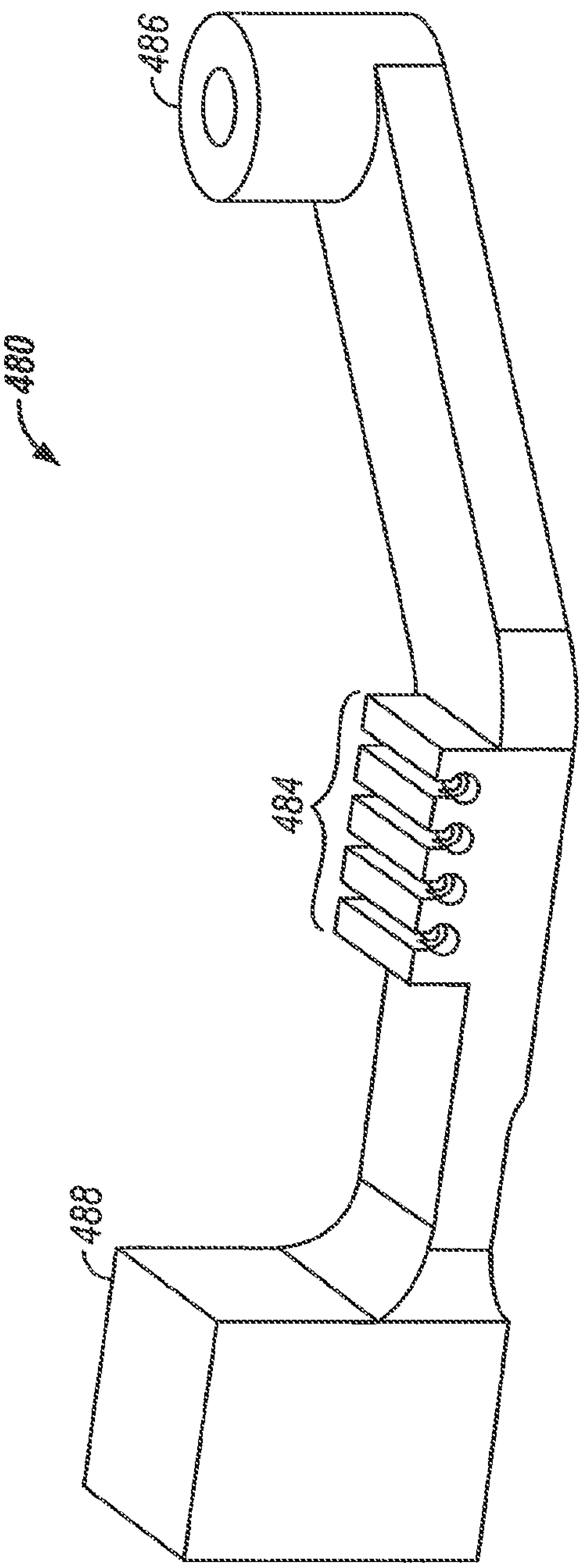

FIG. 43

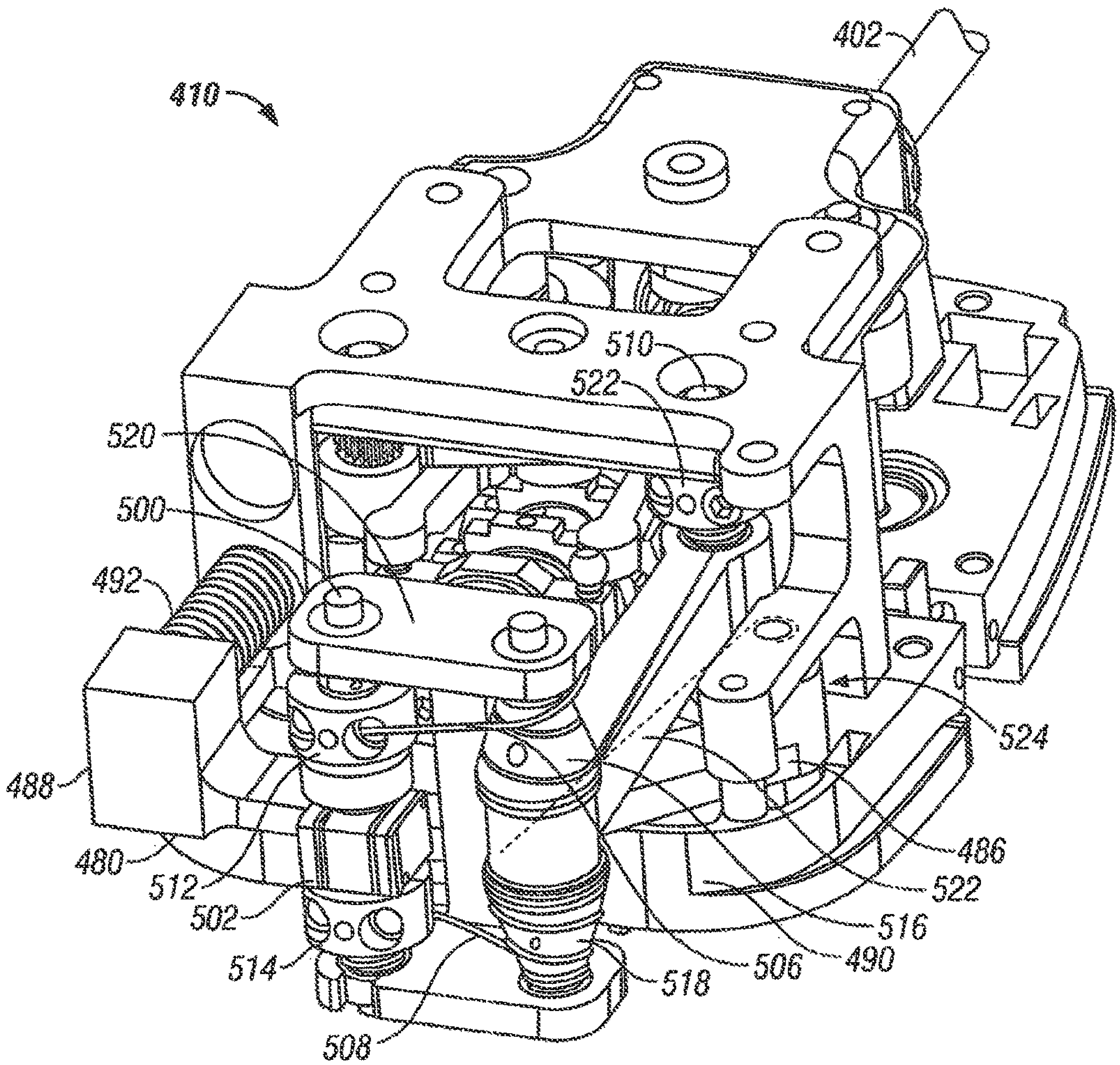
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FIG. 44

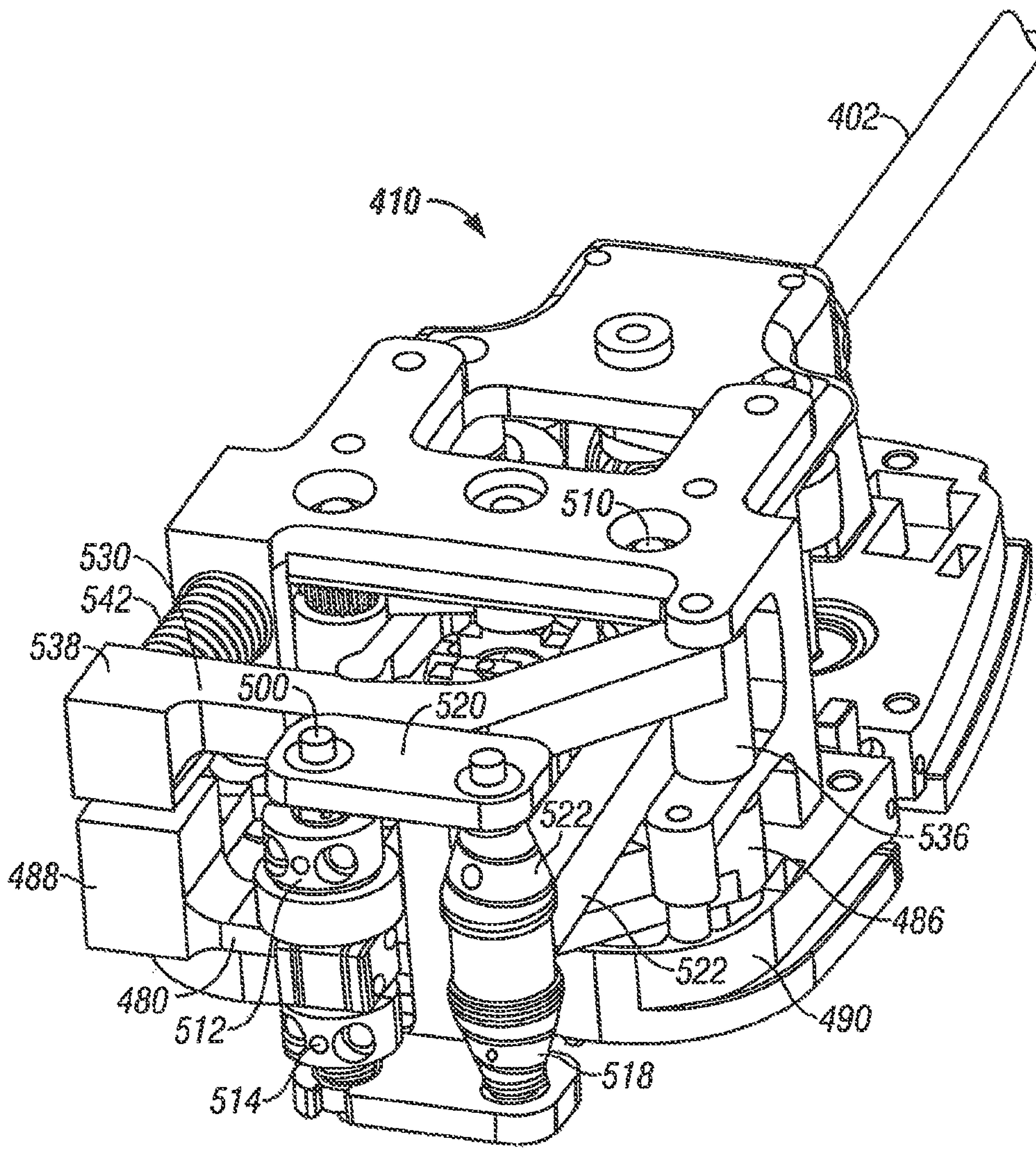
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FIG. 45

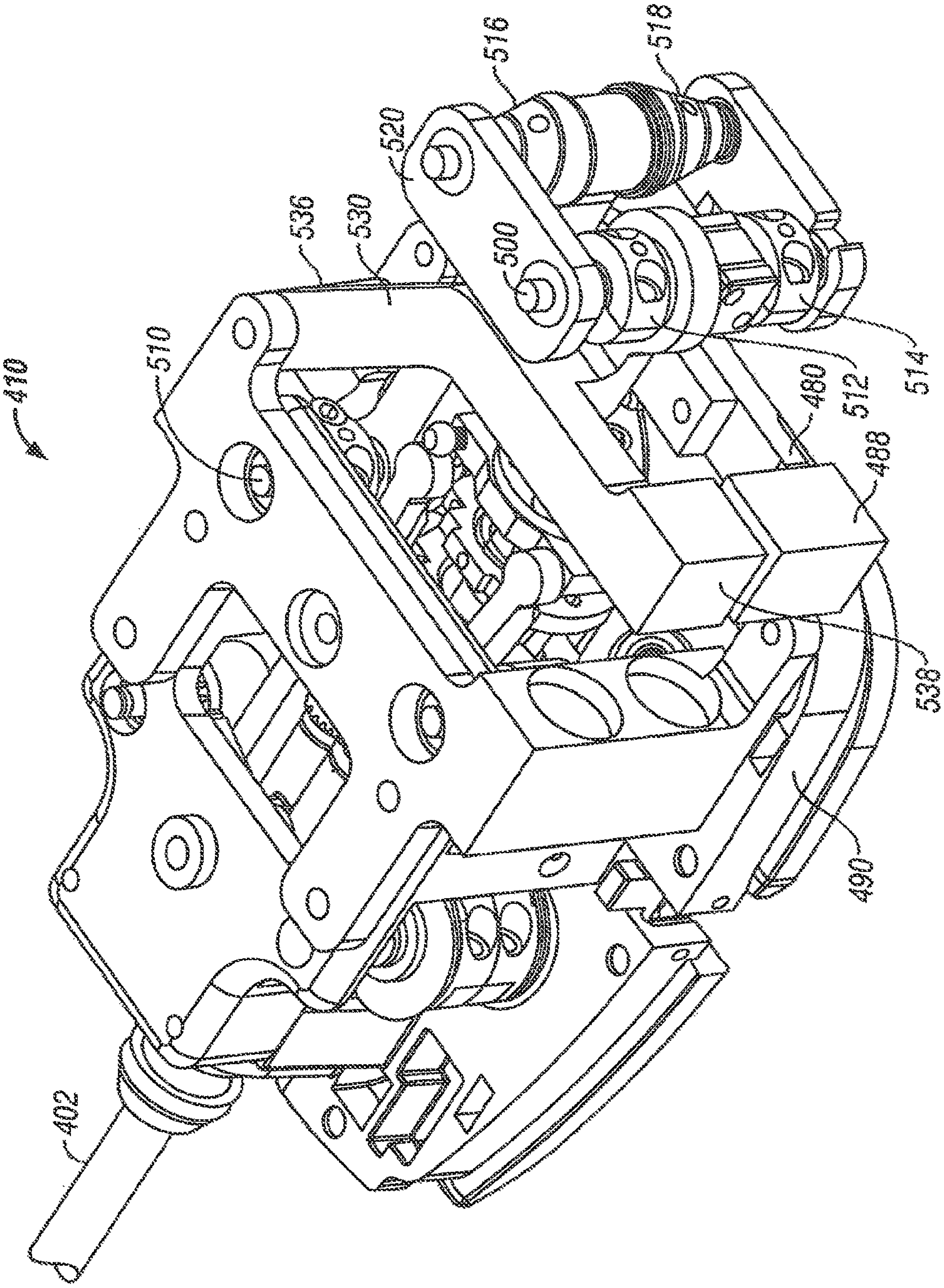

FIG. 46

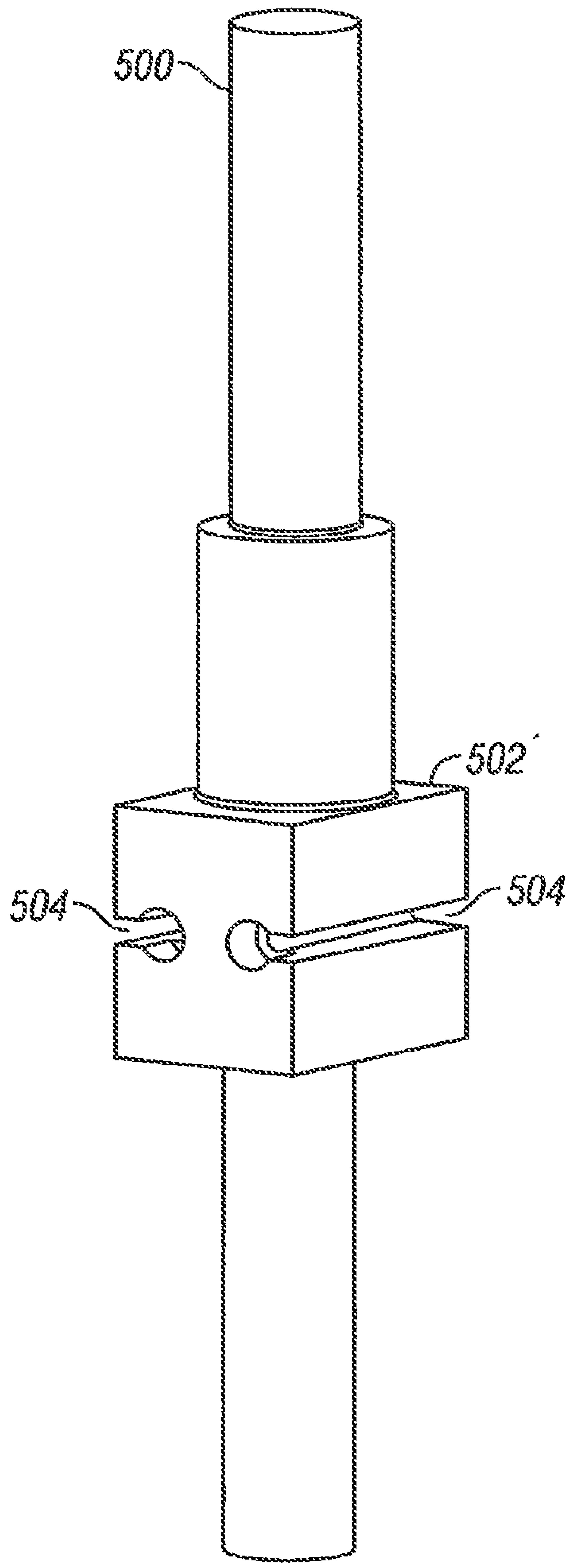

FIG. 47

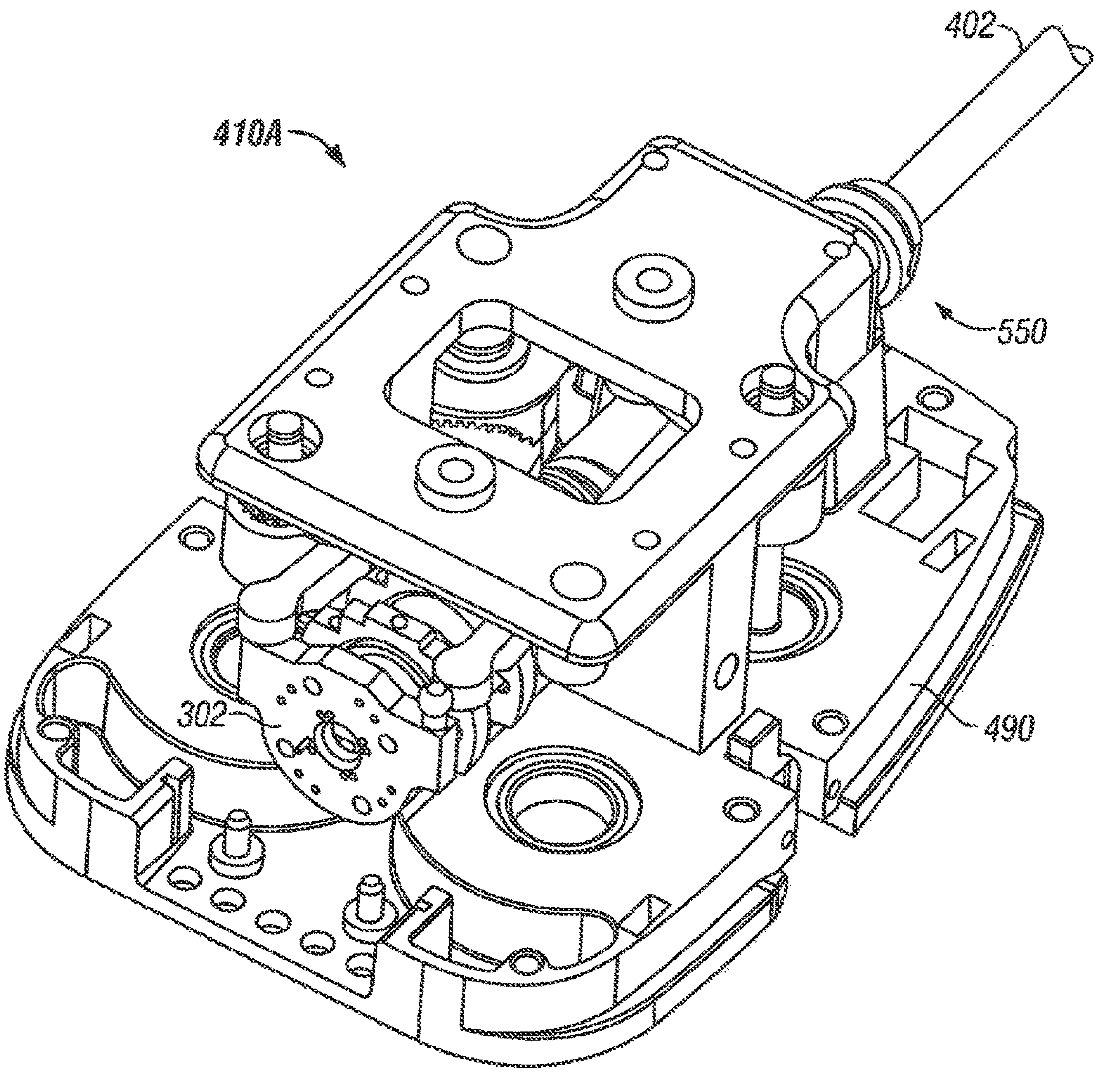

FIG. 48

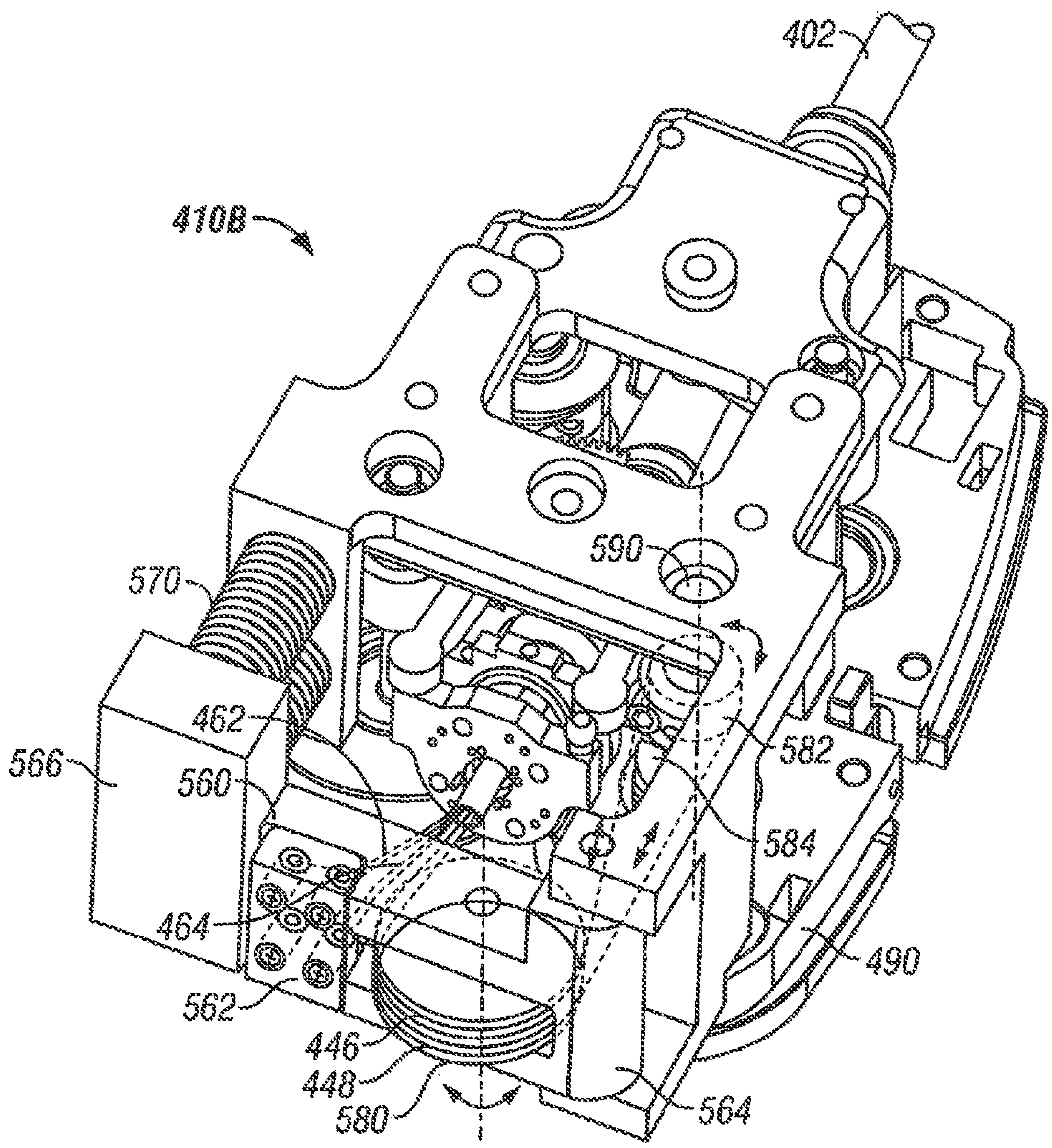

FIG. 49

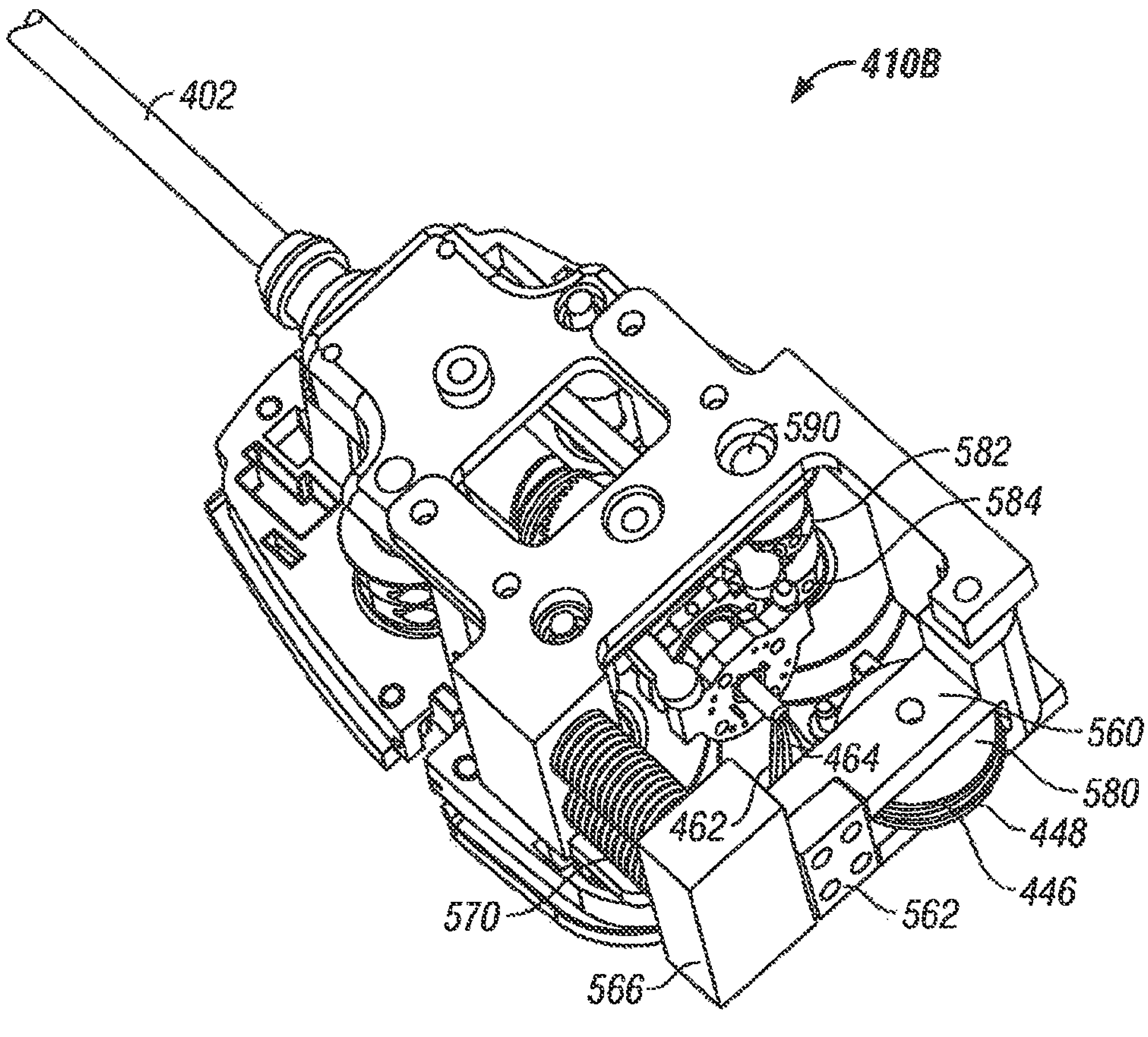

FIG. 50

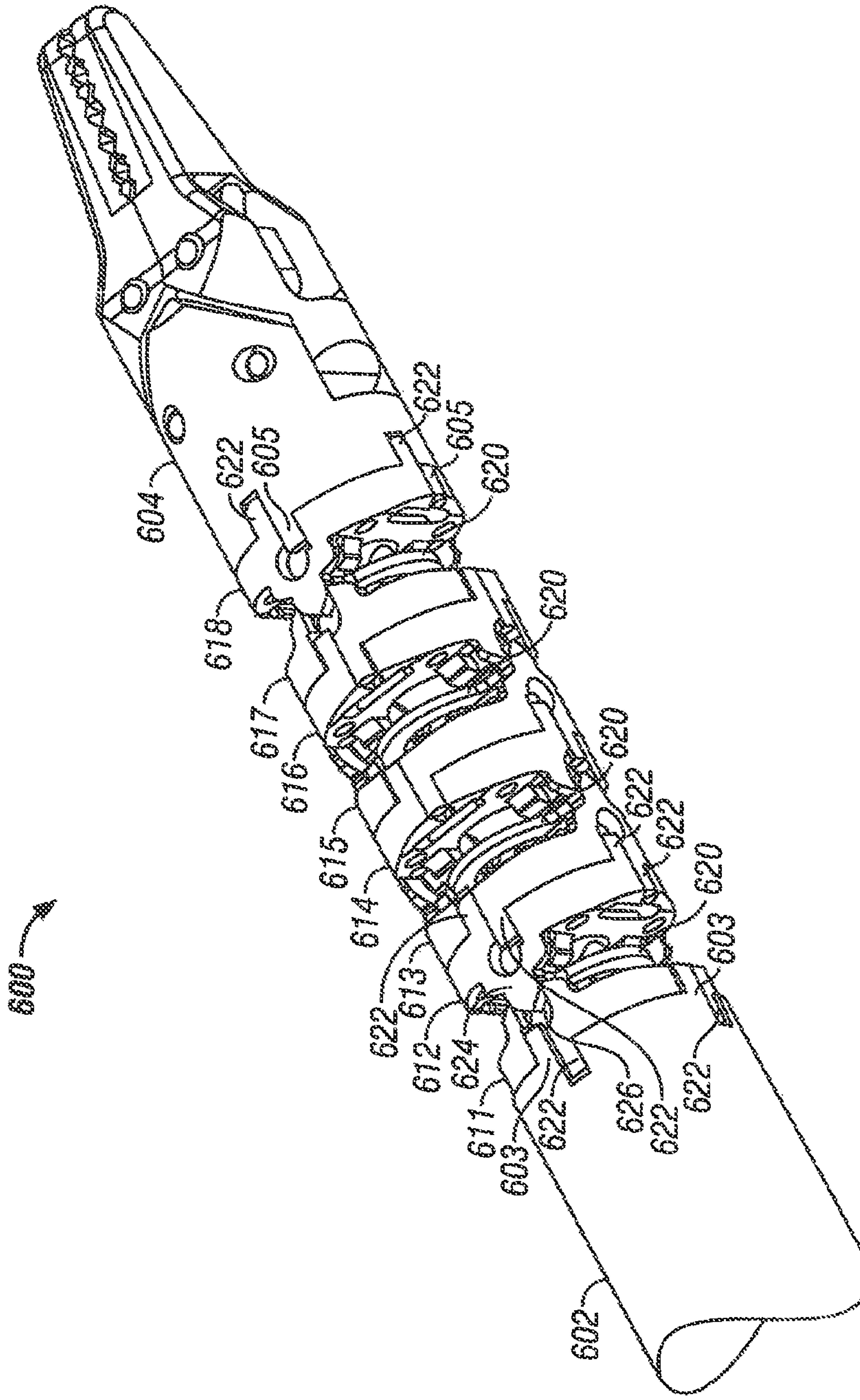
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FIG. 51

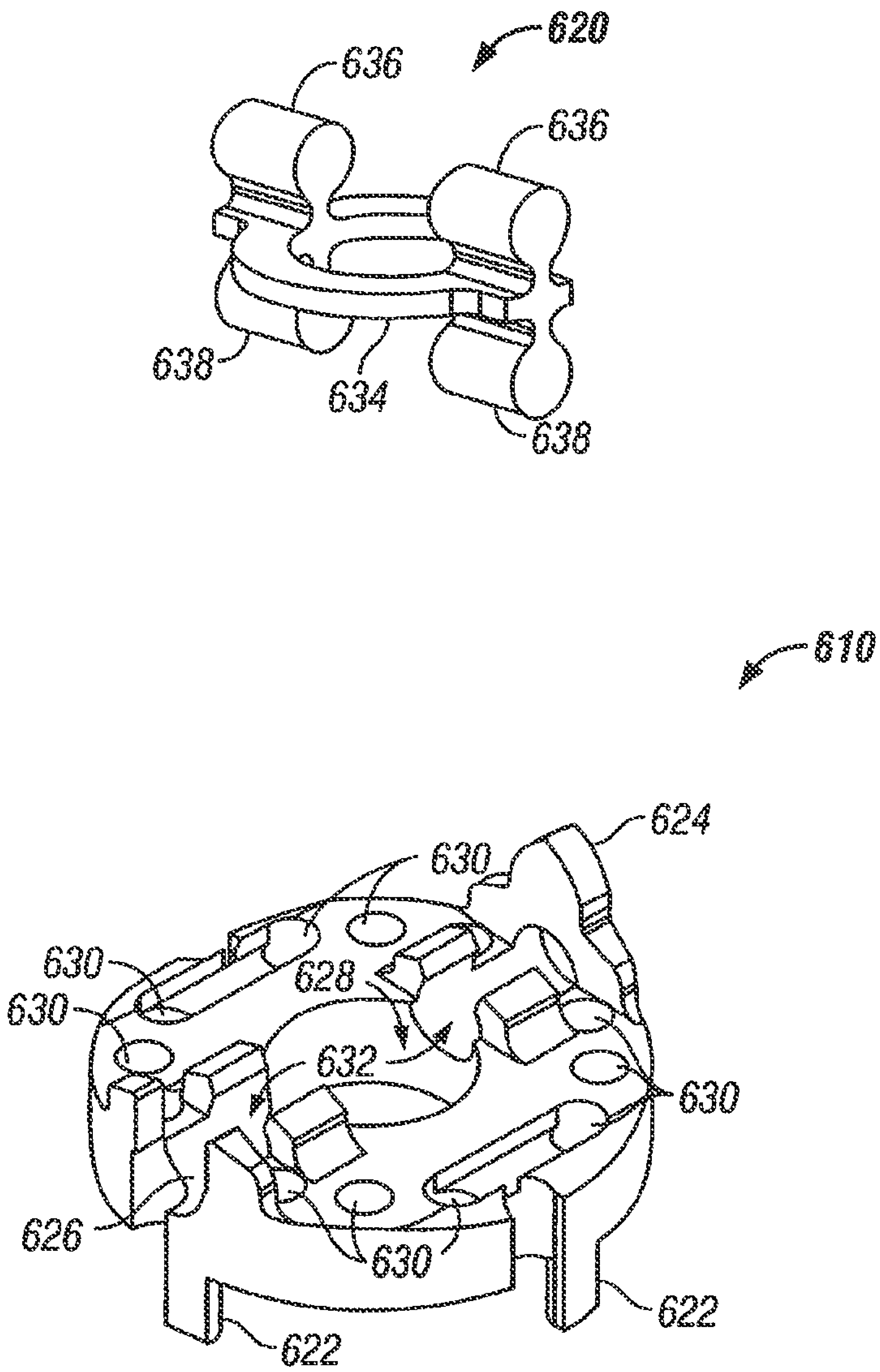

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FIG. 52

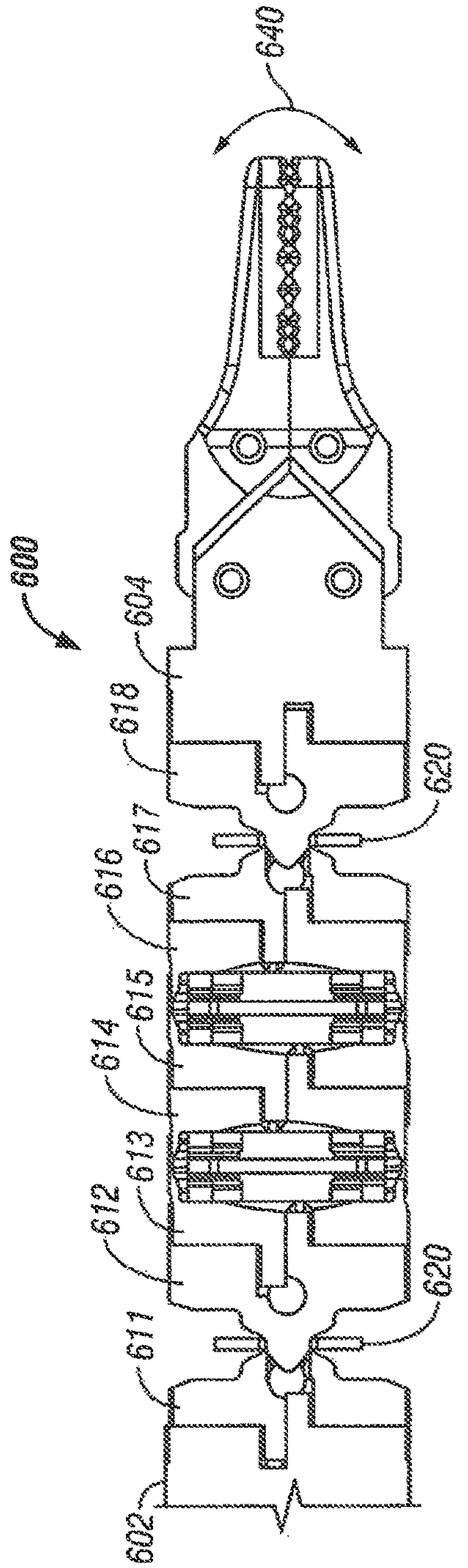
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FIG. 53

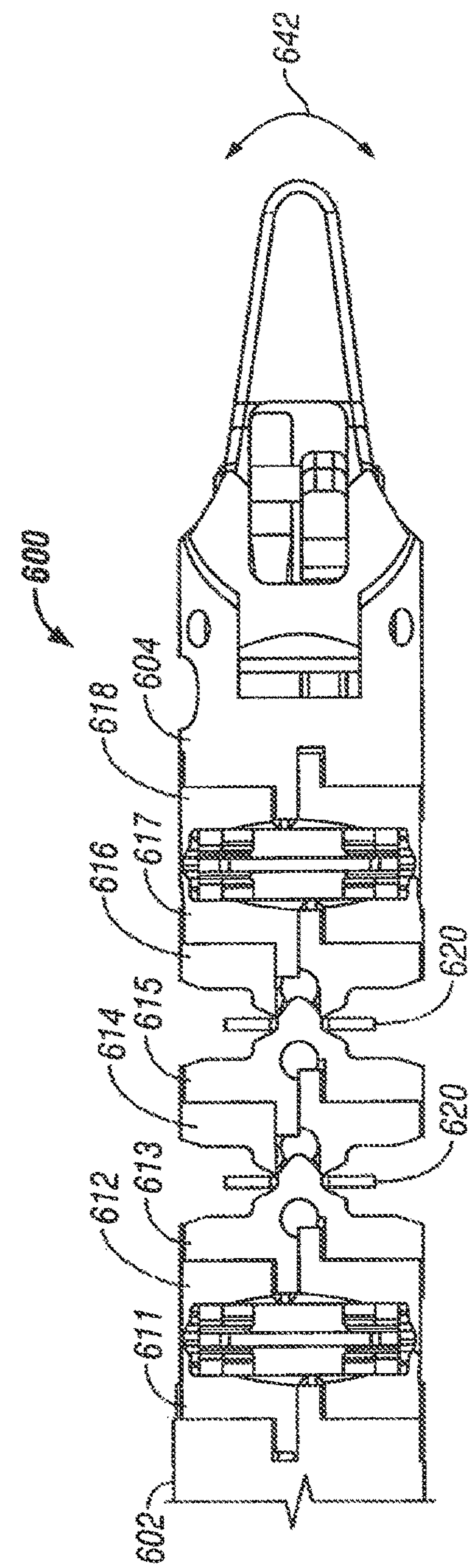
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FIG. 54

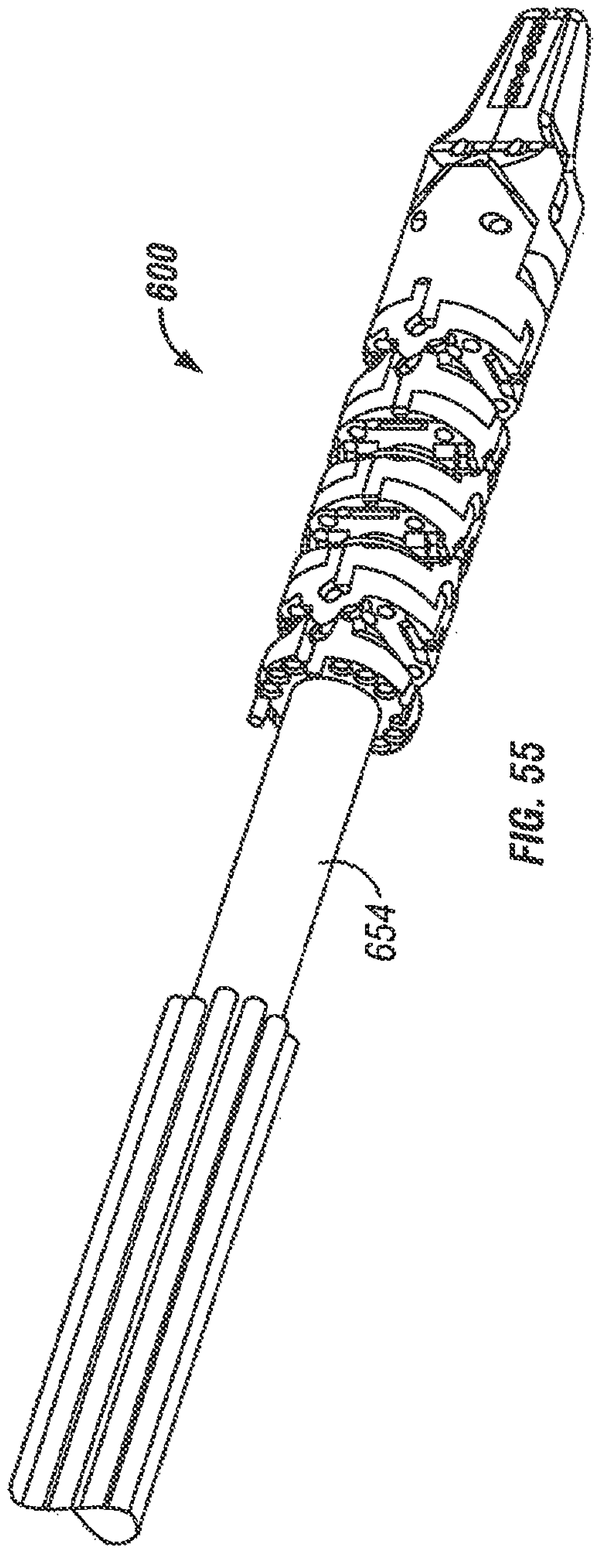

FIG. 55

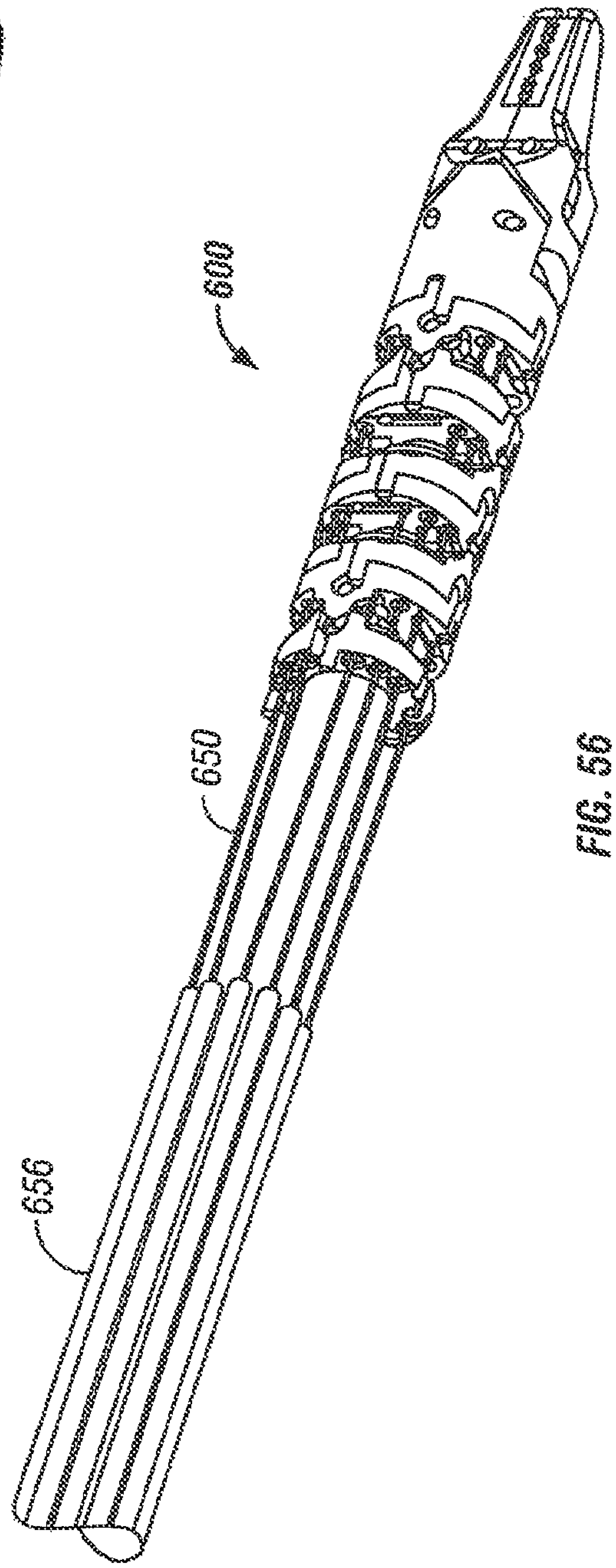

FIG. 56

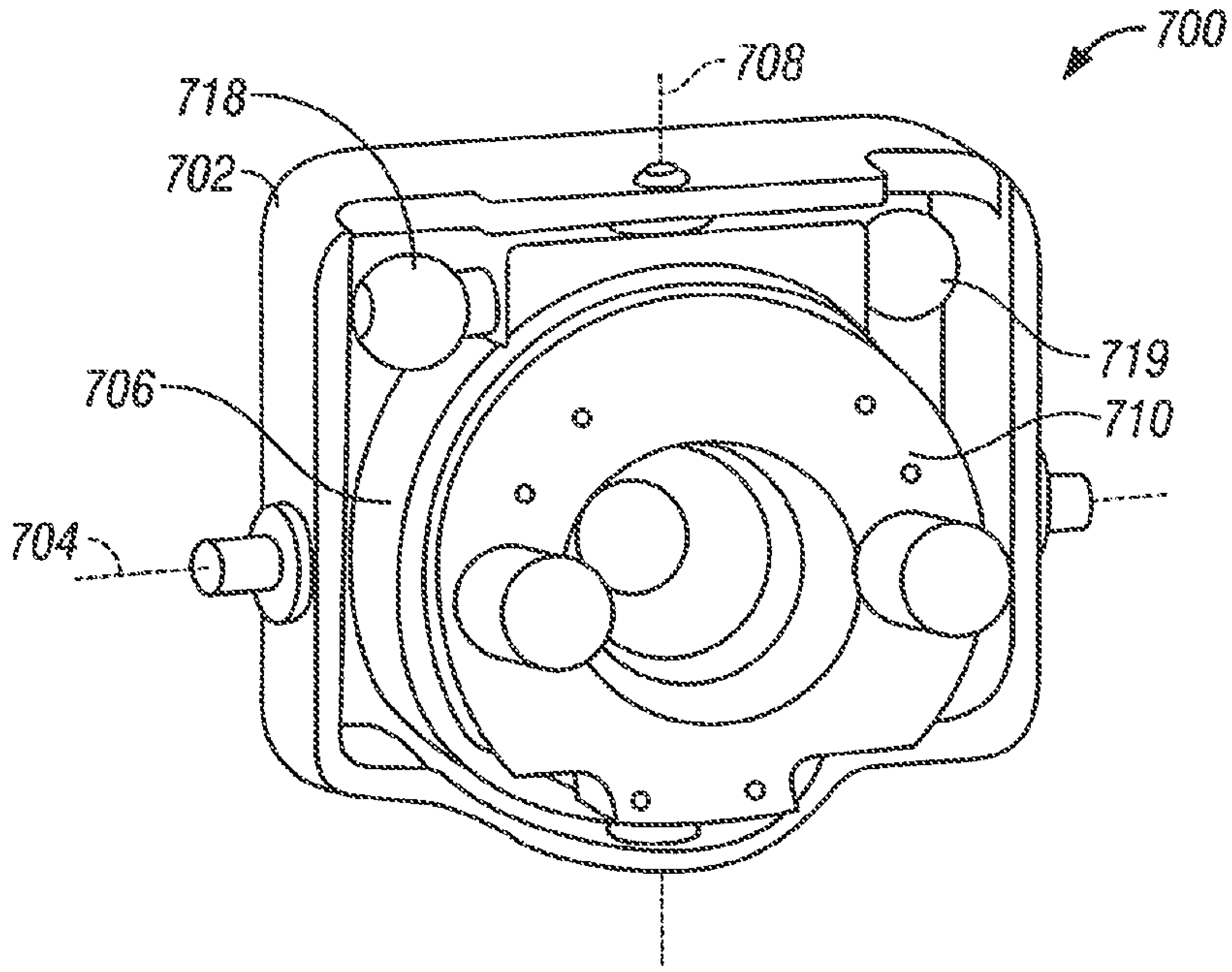

FIG. 57

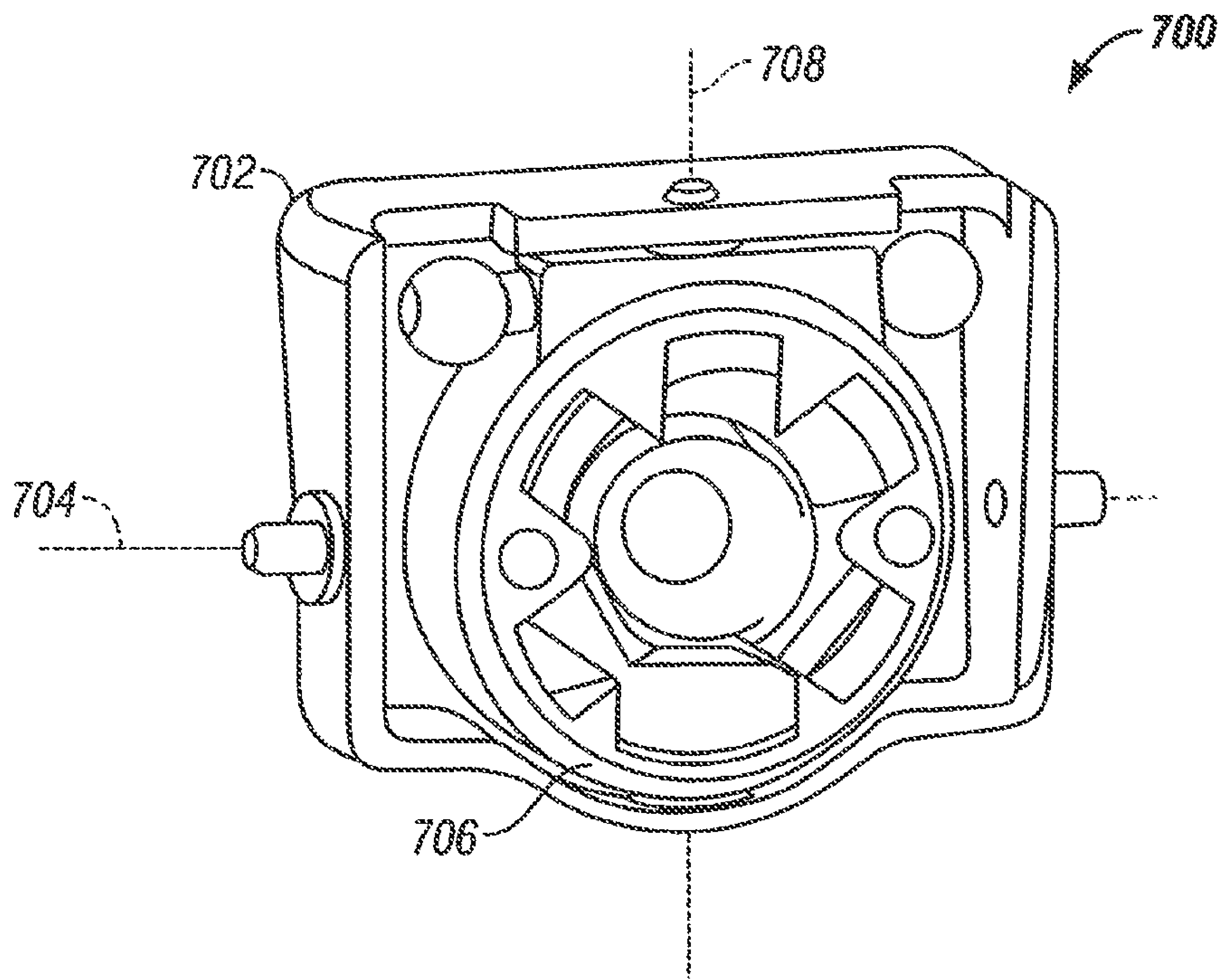

FIG. 58

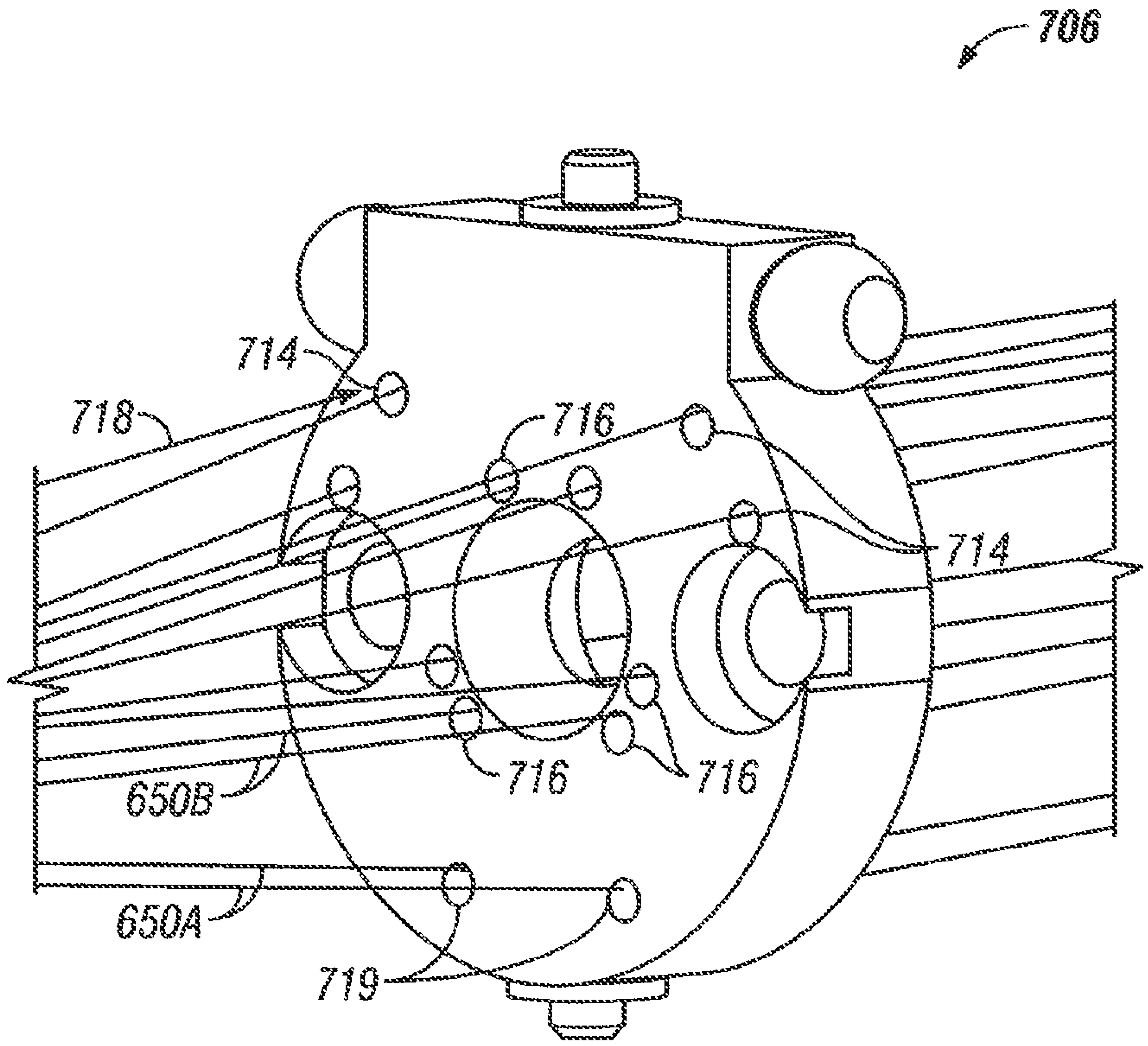

FIG. 59

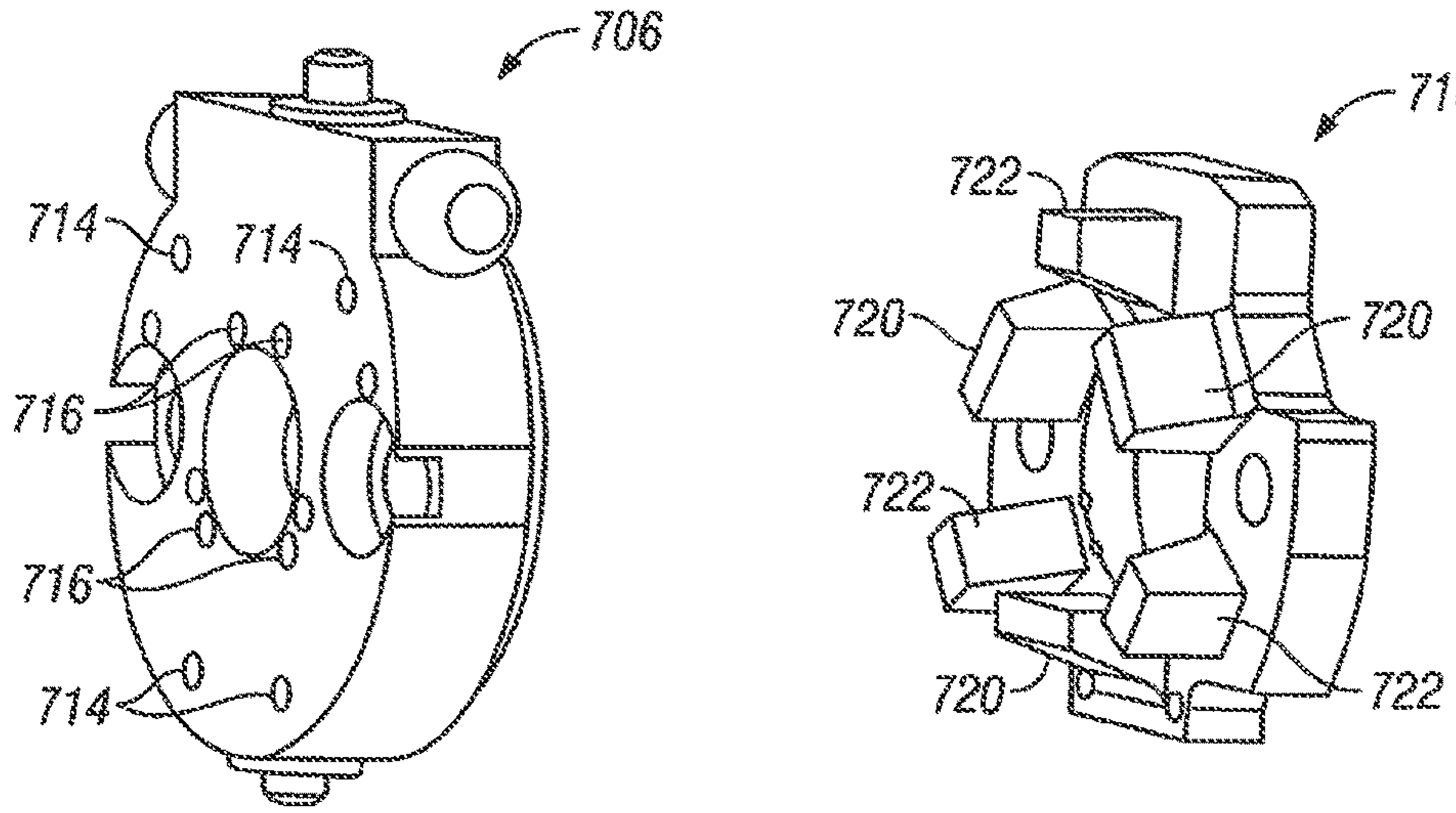

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FIG. 60

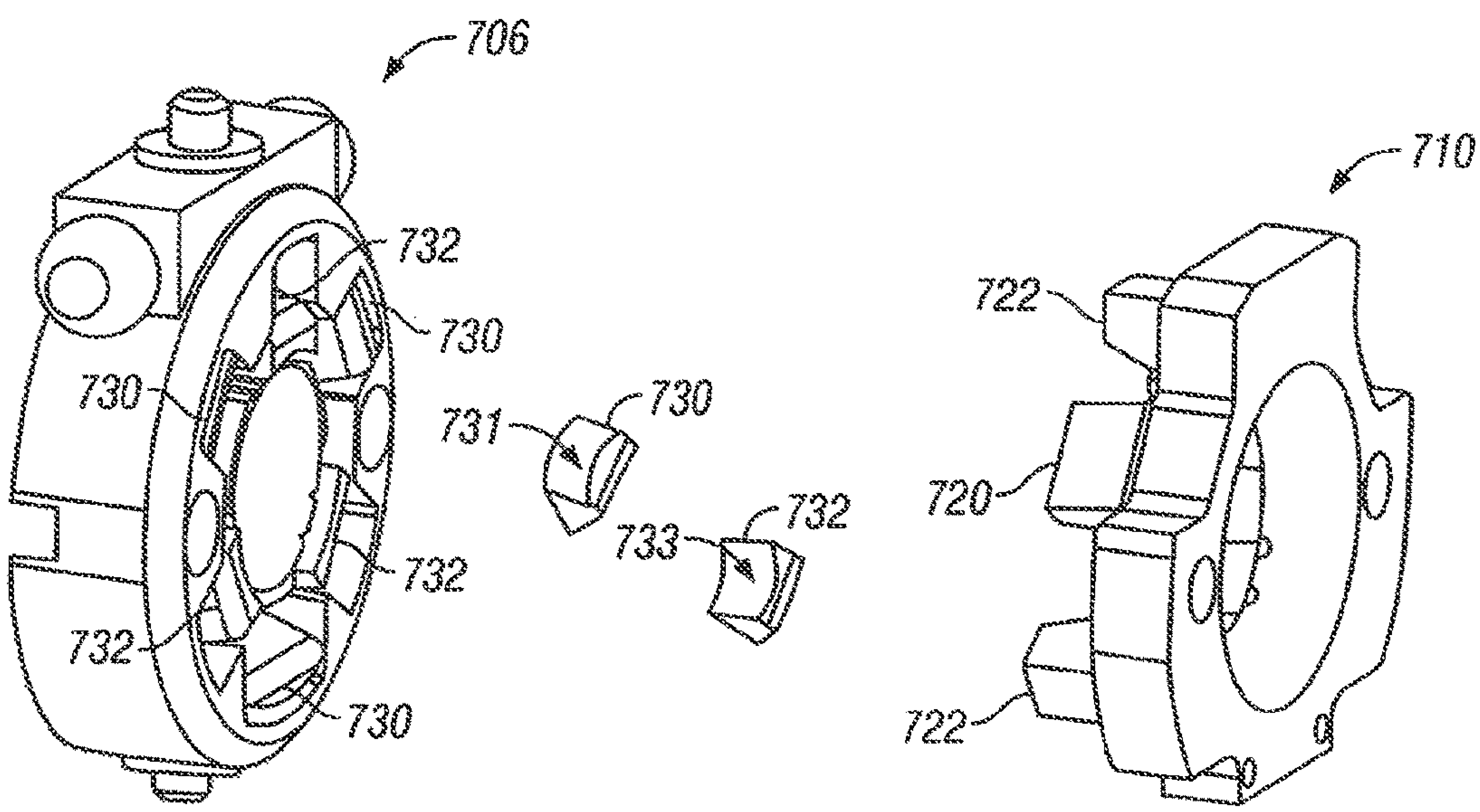

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FIG. 61

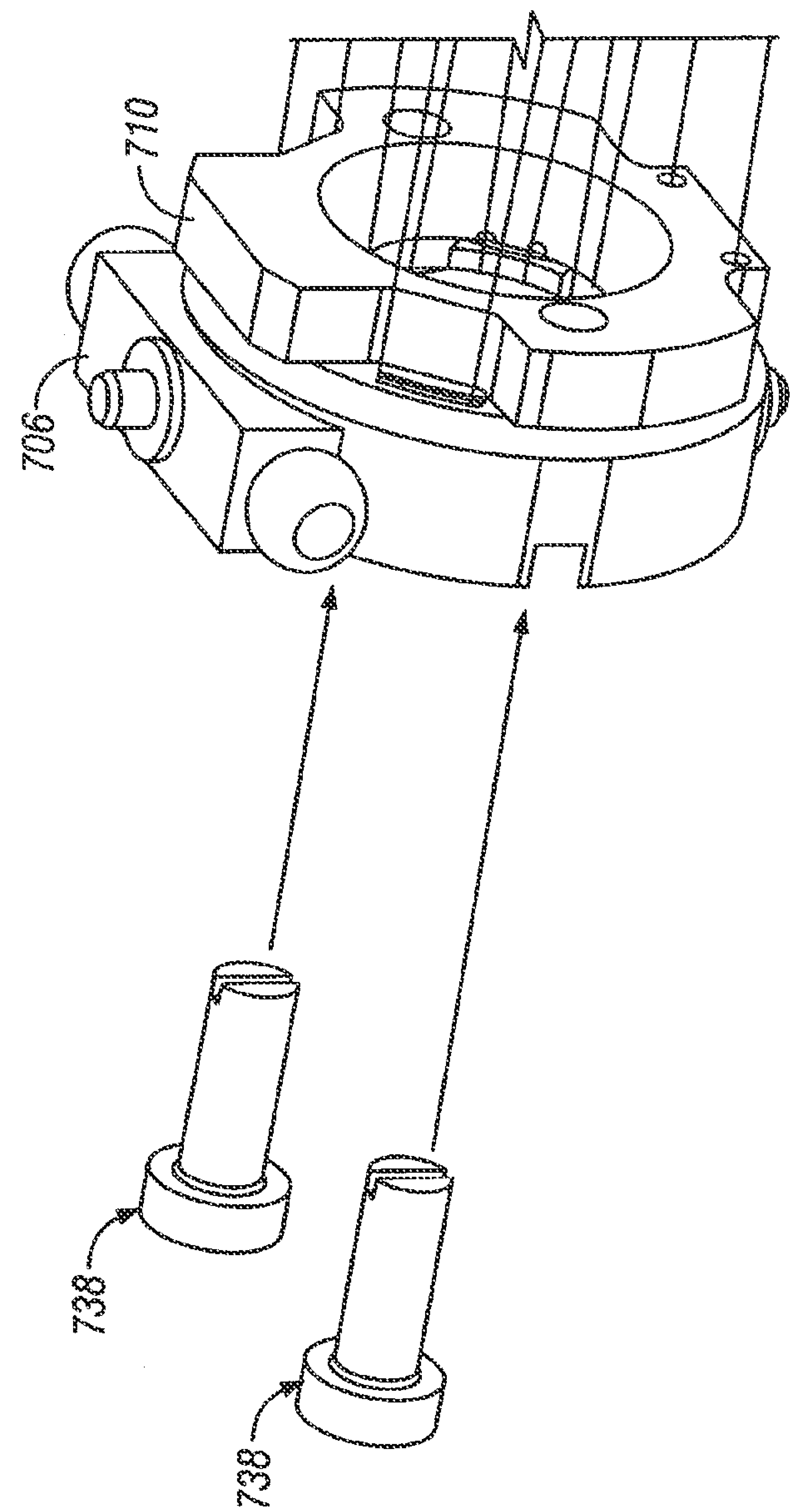

FIG. 62

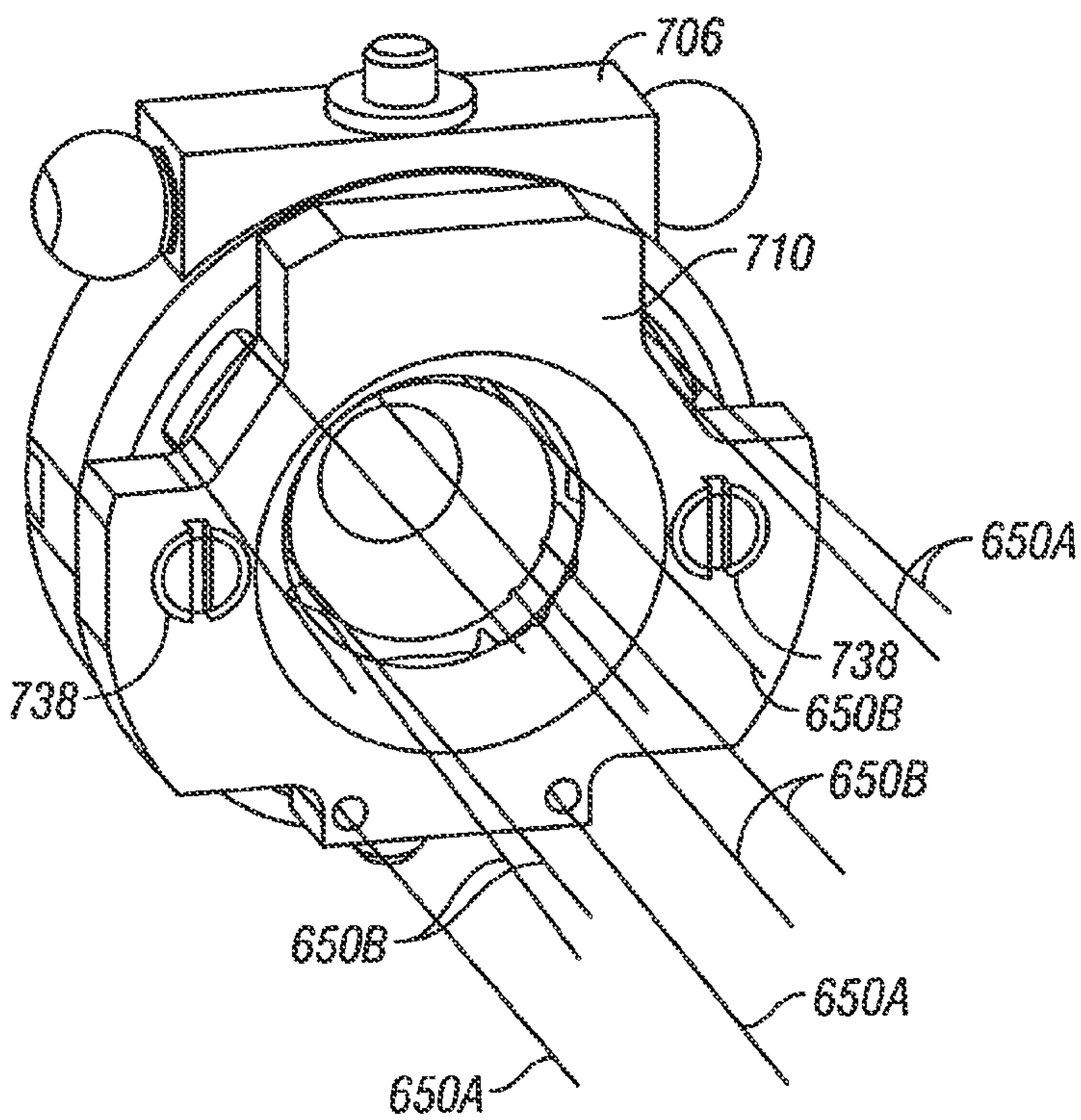

FIG. 63

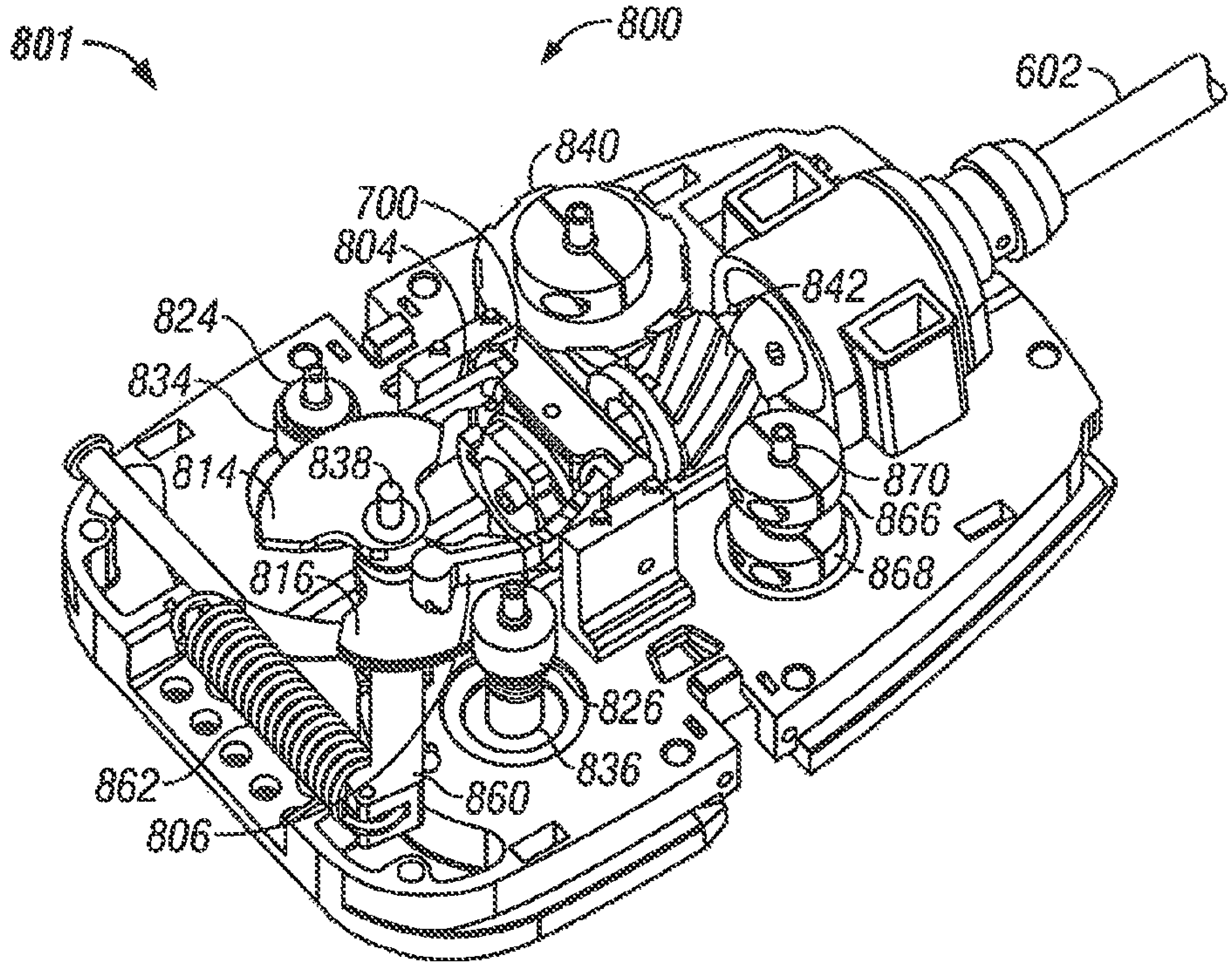
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FIG. 64

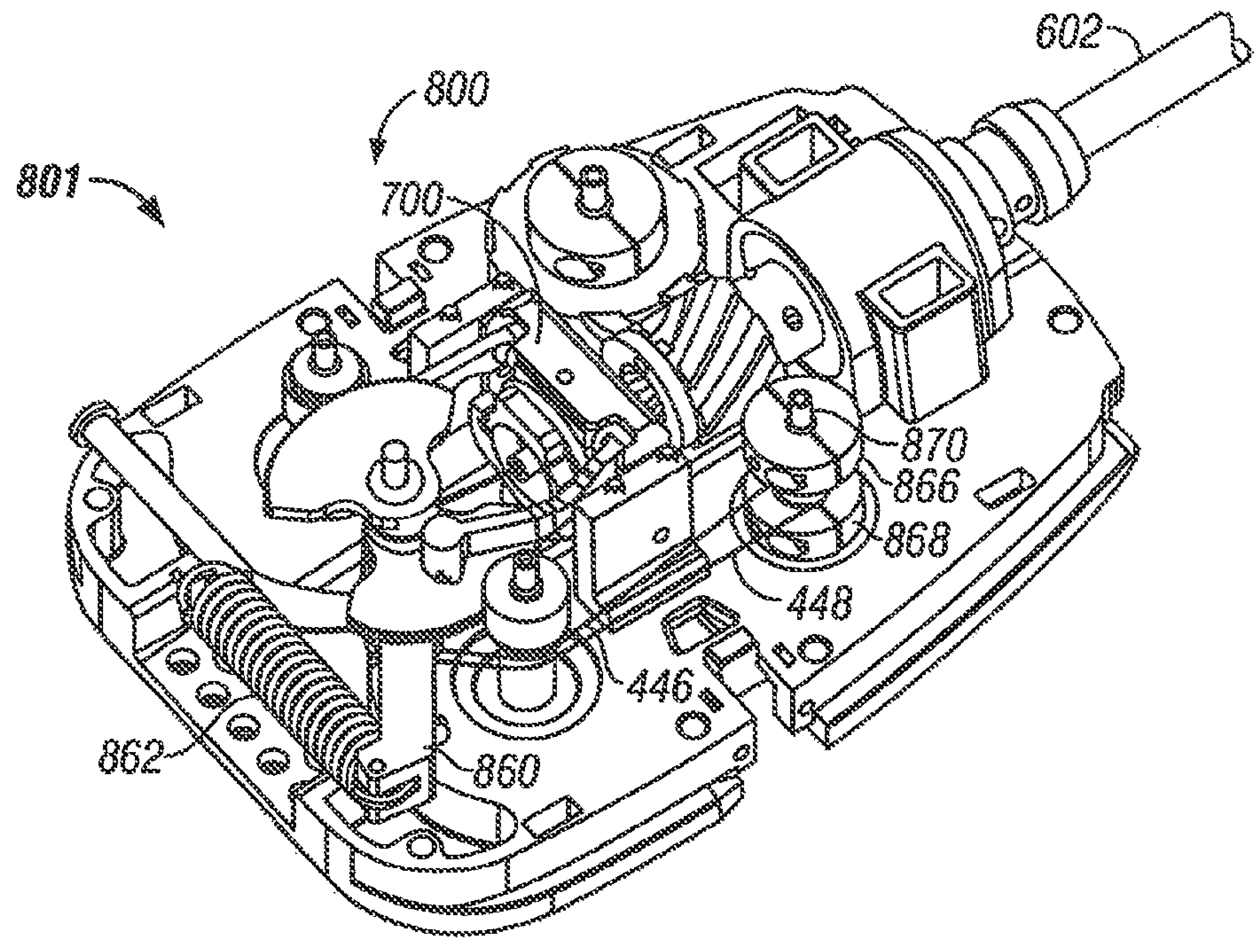
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FIG. 65

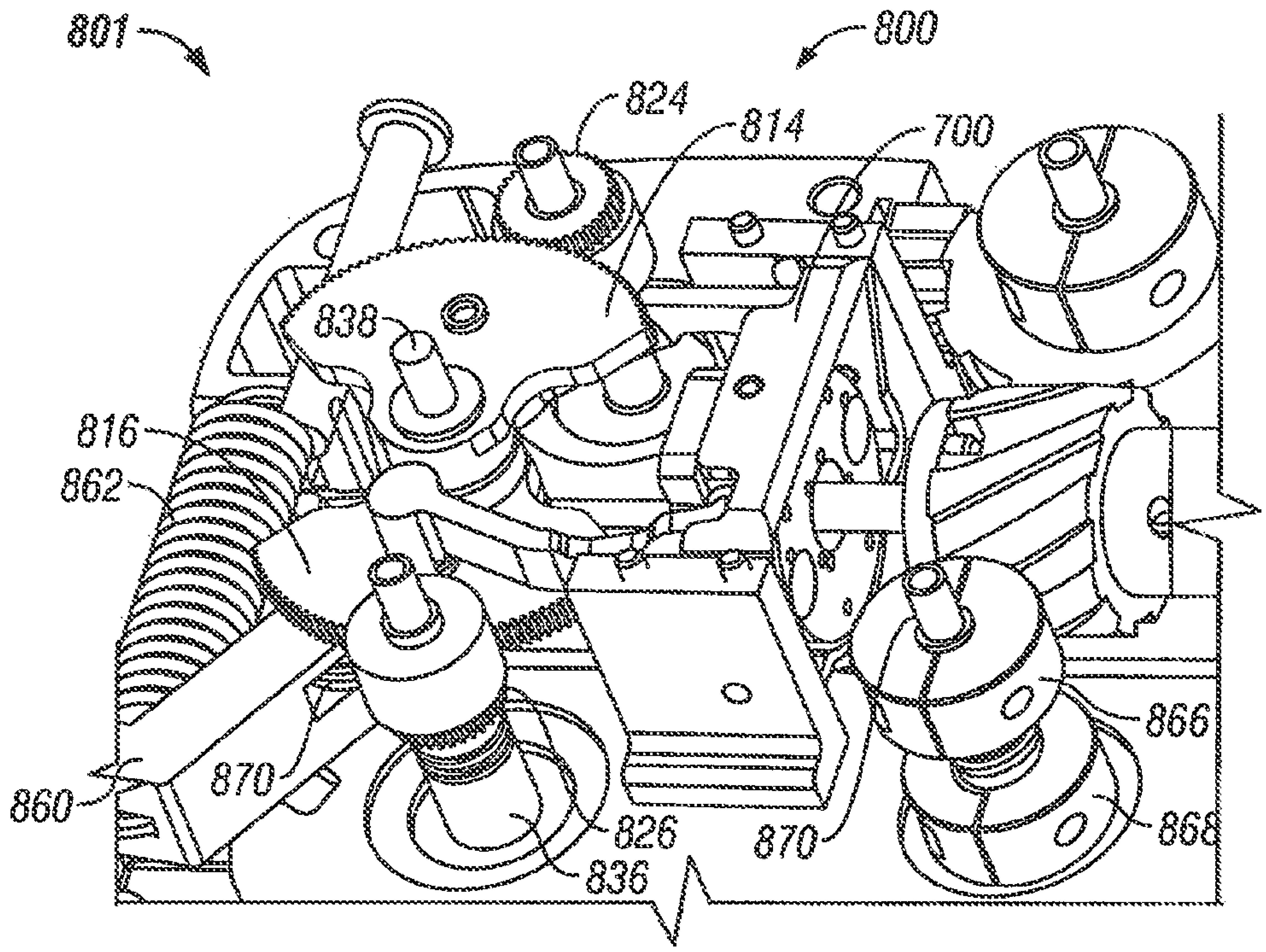
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FIG. 66

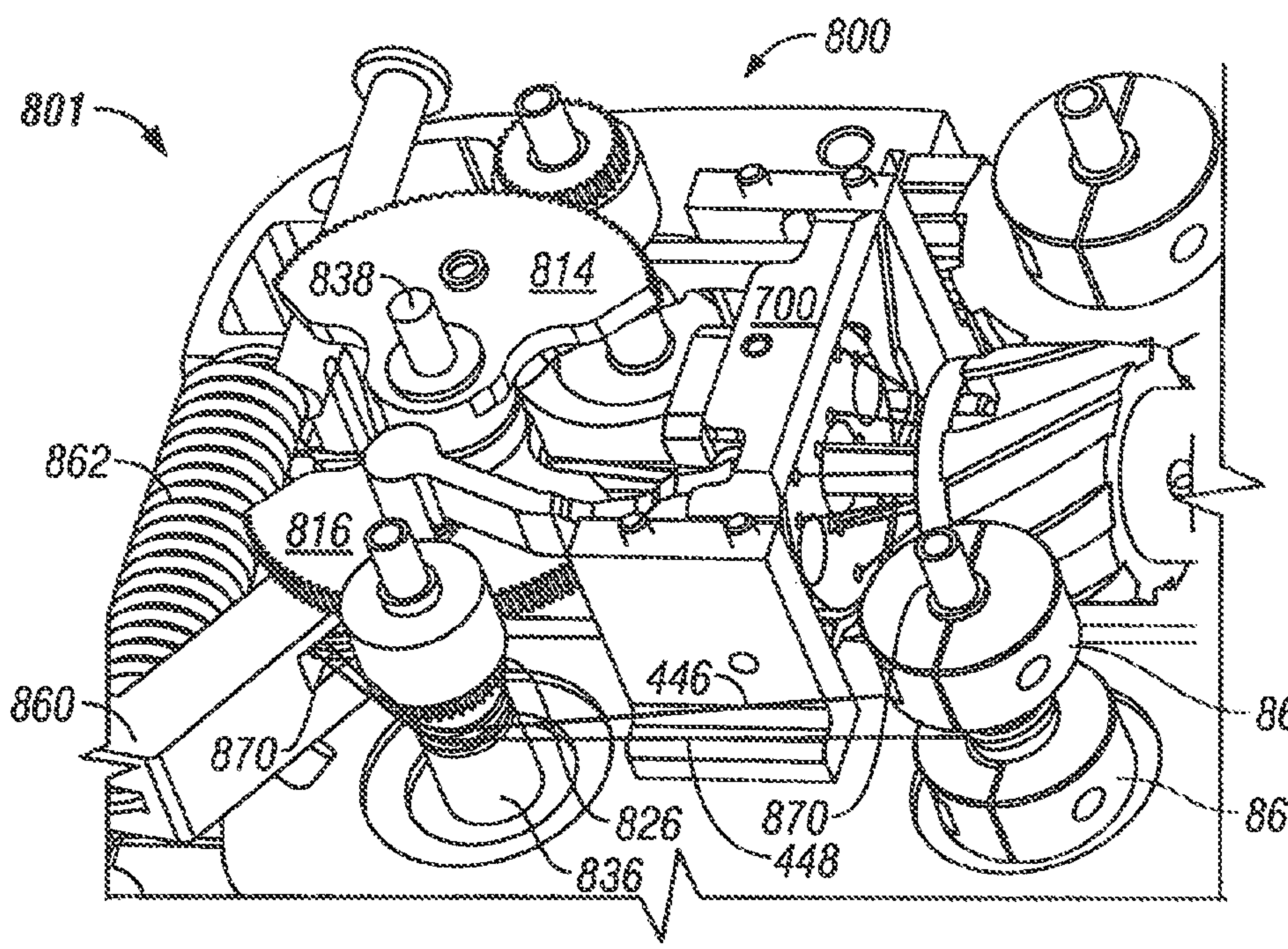
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FIG. 67

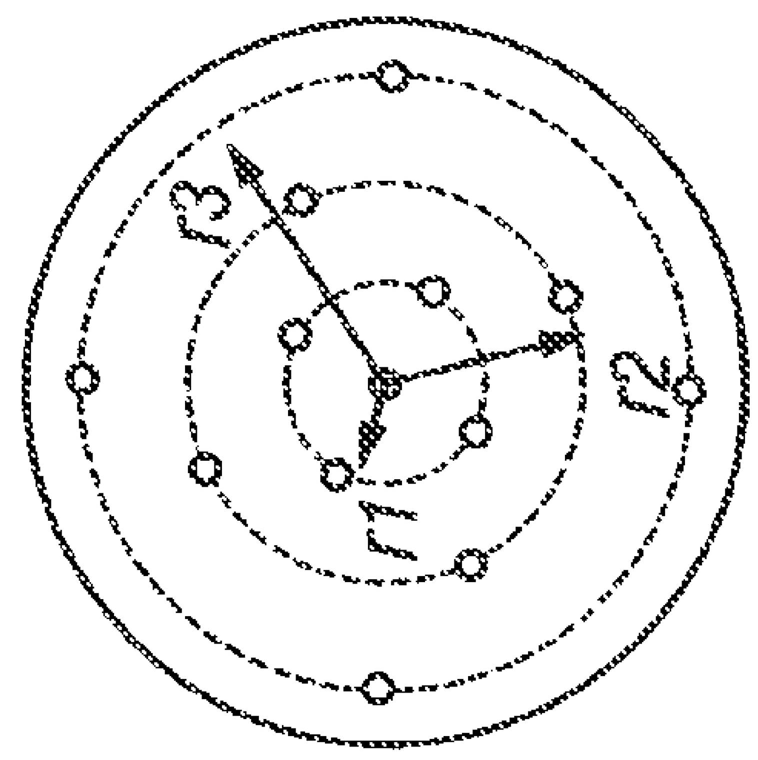

FIG. 68C

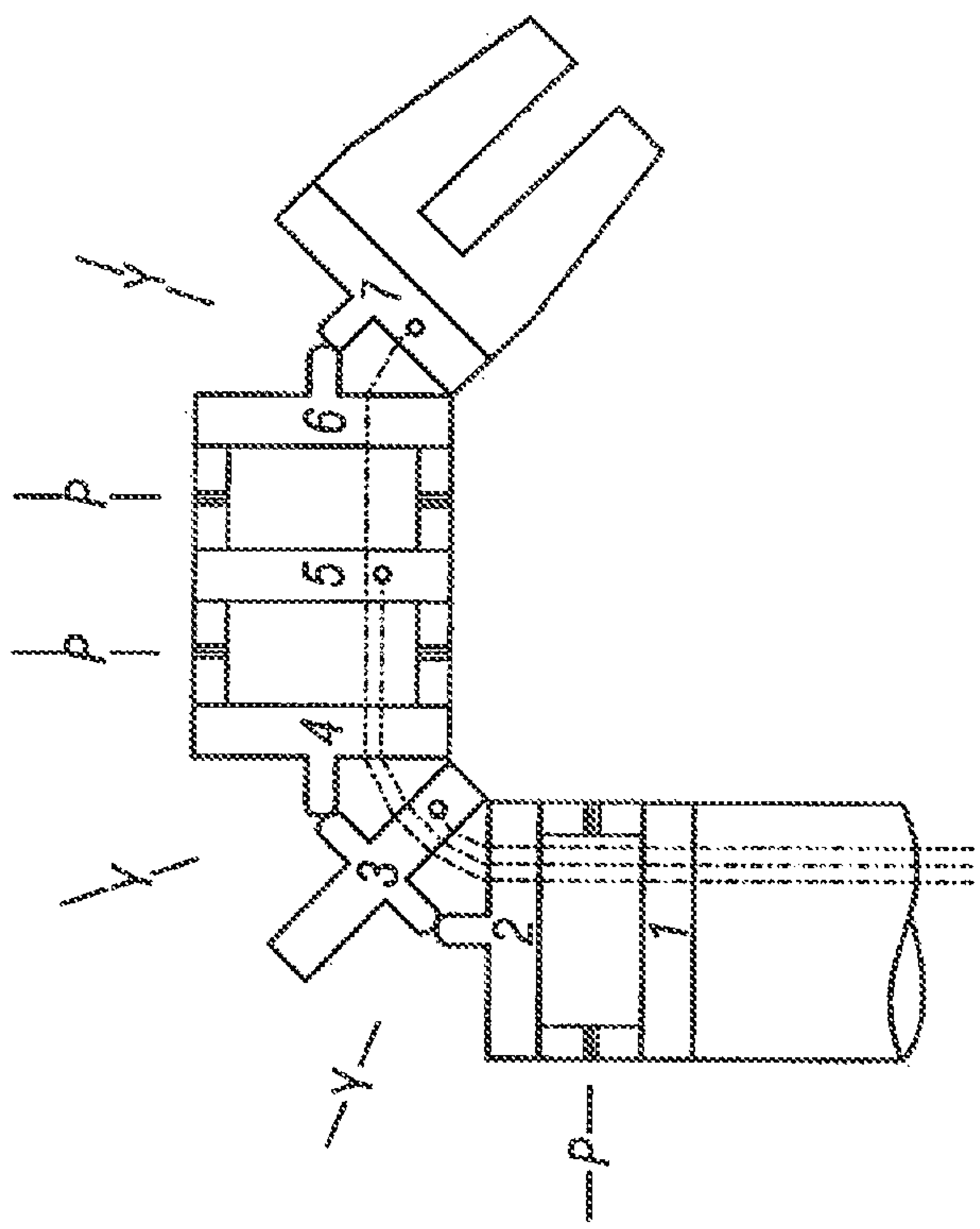

FIG. 68B

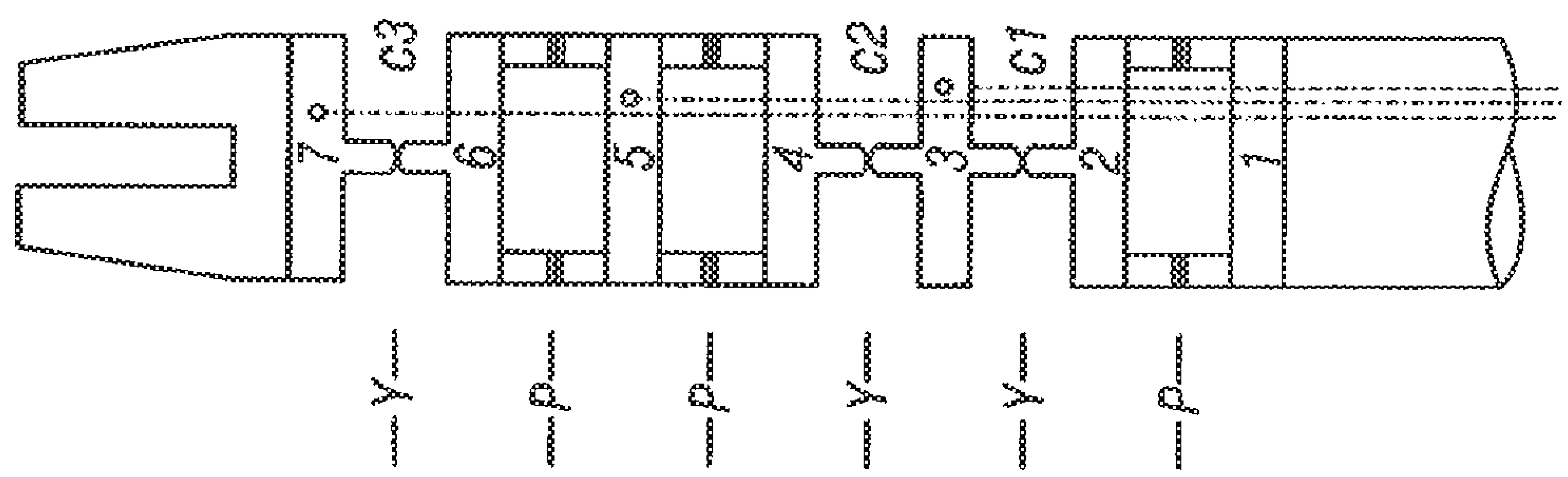

FIG. 68A

APPARATUS FOR PITCH AND YAW ROTATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/536,899, filed Nov. 10, 2014, which is a continuation of U.S. patent application Ser. No. 13/414,445, filed Mar. 7, 2012, now U.S. Pat. No. 8,911,428, which is a continuation of U.S. patent application Ser. No. 12/782,833, filed May 19, 2010, now U.S. Pat. No. 8,142,421, which is a division of U.S. patent application Ser. No. 10/980,119, filed Nov. 1, 2004, now U.S. Pat. No. 7,736,356, which is a division of U.S. patent application Ser. No. 10/187,248, filed Jun. 28, 2002, now U.S. Pat. No. 6,817,974, which is based on and claims the benefit of U.S. Provisional Patent Application No. 60/301,967, filed Jun. 29, 2001, and U.S. Provisional Patent Application No. 60/327,702, filed Oct. 5, 2001, the entire disclosures of which are incorporated herein by reference.

This application is related to the following patents and patent applications, the full disclosures of which are incorporated herein by reference:

PCT International Application No. PCT/US98/19508, entitled "Robotic Apparatus", filed on Sep. 18, 1998, and published as WO99/50721;

U.S. patent application Ser. No. 09/418,726, entitled "Surgical Robotic Tools, Data Architecture, and Use", filed on Oct. 15, 1999;

U.S. patent application Ser. No. 60/111,711, entitled "Image Shifting for a Telerobotic System", filed on Dec. 8, 1998;

U.S. patent application Ser. No. 09/378,173, entitled "Stereo Imaging System for Use in Telerobotic System", filed on Aug. 20, 1999;

U.S. patent application Ser. No. 09/398,507, entitled "Master Having Redundant Degrees of Freedom", filed on Sep. 17, 1999;

U.S. application Ser. No. 09/399,457, entitled "Cooperative Minimally Invasive Telesurgery System", filed on Sep. 17, 1999;

U.S. patent application Ser. No. 09/373,678, entitled "Camera Referenced Control in a Minimally Invasive Surgical Apparatus", filed on Aug. 13, 1999;

U.S. patent application Ser. No. 09/398,958, entitled "Surgical Tools for Use in Minimally Invasive Telesurgical Applications", filed on Sep. 17, 1999; and

U.S. Pat. No. 5,808,665, entitled "Endoscopic Surgical Instrument and Method for Use", issued on Sep. 15, 1998.

BACKGROUND OF THE INVENTION

The present invention relates generally to surgical tools and, more particularly, to various wrist mechanisms in surgical tools for performing robotic surgery.

Advances in minimally invasive surgical technology could dramatically increase the number of surgeries performed in a minimally invasive manner Minimally invasive medical techniques are aimed at reducing the amount of extraneous tissue that is damaged during diagnostic or surgical procedures, thereby reducing patient recovery time, discomfort, and deleterious side effects. The average length of a hospital stay for a standard surgery may also be shortened significantly using minimally invasive surgical techniques. Thus, an increased adoption of minimally invasive techniques could save millions of hospital days, and millions of dollars annually in hospital residency costs alone. Patient recovery times, patient discomfort, surgical side effects, and time away from work may also be reduced with minimally invasive surgery.

The most common form of minimally invasive surgery may be endoscopy. Probably the most common form of endoscopy is laparoscopy, which is minimally invasive inspection and surgery inside the abdominal cavity. In standard laparoscopic surgery, a patient's abdomen is insufflated with gas, and cannula sleeves are passed through small (approximately ½ inch) incisions to provide entry ports for laparoscopic surgical instruments. The laparoscopic surgical instruments generally include a laparoscope (for viewing the surgical field) and working tools. The working tools are similar to those used in conventional (open) surgery, except that the working end or end effector of each tool is separated from its handle by an extension tube. As used herein, the term "end effector" means the actual working part of the surgical instrument and can include clamps, graspers, scissors, staplers, and needle holders, for example. To perform surgical procedures, the surgeon passes these working tools or instruments through the cannula sleeves to an internal surgical site and manipulates them from outside the abdomen. The surgeon monitors the procedure by means of a monitor that displays an image of the surgical site taken from the laparoscope. Similar endoscopic techniques are employed in, e.g., arthroscopy, retroperitoneoscopy, pelviscopy, nephroscopy, cystoscopy, cisternoscopy, sinoscopy, hysteroscopy, urethroscopy and the like.

There are many disadvantages relating to current minimally invasive surgical (MIS) technology. For example, existing MIS instruments deny the surgeon the flexibility of tool placement found in open surgery. Most current laparoscopic tools have rigid shafts, so that it can be difficult to approach the worksite through the small incision. Additionally, the length and construction of many endoscopic instruments reduces the surgeon's ability to feel forces exerted by tissues and organs on the end effector of the associated tool. The lack of dexterity and sensitivity of endoscopic tools is a major impediment to the expansion of minimally invasive surgery.

Minimally invasive telesurgical robotic systems are being developed to increase a surgeon's dexterity when working within an internal surgical site, as well as to allow a surgeon to operate on a patient from a remote location. In a telesurgery system, the surgeon is often provided with an image of the surgical site at a computer workstation. While viewing a three-dimensional image of the surgical site on a suitable viewer or display, the surgeon performs the surgical procedures on the patient by manipulating master input or control devices of the workstation. The master controls the motion of a servomechanically operated surgical instrument. During the surgical procedure, the telesurgical system can provide mechanical actuation and control of a variety of surgical instruments or tools having end effectors such as, e.g., tissue graspers, needle drivers, or the like, that perform various functions for the surgeon, e.g., holding or driving a needle, grasping a blood vessel, or dissecting tissue, or the like, in response to manipulation of the master control devices.

Some surgical tools employ a roll-pitch-yaw mechanism for providing three degrees of rotational movement to an end effector around three perpendicular axes. The pitch and yaw rotations are typically provided by a wrist mechanism coupled between a shaft of the tool and an end effector, and the roll rotation is typically provided by rotation of the shaft. At about 90° pitch, the yaw and roll rotational movements overlap, resulting in the loss of one degree of rotational movement, referred to as a singularity.

BRIEF SUMMARY OF THE INVENTION

The present invention is directed to alternative embodiments of a tool having a wrist mechanism that provides pitch and yaw rotation in such a way that the tool has no singularity in roll, pitch, and yaw. In one preferred embodiment, a wrist mechanism includes a plurality of disks or vertebrae stacked or coupled in series. Typically the most proximal vertebrae or disk of the stack is coupled to a proximal end member segment, such as the working end of a tool or instrument shaft; and the most distal vertebrae or disk is coupled to a distal end member segment, such as an end-effector or end-effector support member. Each disk is configured to rotate in at least one degree of freedom or DOF (e.g., in pitch or in yaw) with respect to each neighboring disk or end member.

In general, in the discussion herein, the term disk or vertebrae may include any proximal or distal end members, unless the context indicates reference to an intermediate segment disposed between the proximal and distal end members. Likewise, the terms disk or vertebrae will be used interchangeably herein to refer to the segment member or segment subassembly, it being understood that the wrist mechanisms having aspects of the invention may include segment members or segment subassemblies of alternative shapes and configurations, which are not necessarily disk-like in general appearance.

Actuation cables or tendon elements are used to manipulate and control movement of the disks, so as to effect movement of the wrist mechanism. The wrist mechanism resembles in some respects tendon-actuated steerable members such as are used in gastroscopes and similar medical instruments. However, multi-disk wrist mechanisms having aspects of the invention may include a number of novel aspects. For example, a wrist embodiment may be positively positionable, and provides that each disk rotates through a positively determinable angle and orientation. For this reason, this embodiment is called a positively positionable multi-disk wrist (PPMD wrist).

In some of the exemplary embodiments having aspects of the invention, each disk is configured to rotate with respect to a neighboring disk by a nonattached contact. As used herein, a nonattached contact refers to a contact that is not attached or joined by a fastener, a pivot pin, or another joining member. The disks maintain contact with each other by, for example, the tension of the actuation cables. The disks are free to separate upon release of the tension of the actuation cables. A nonattached contact may involve rolling and/or sliding between the disks, and/or between a disk and an adjacent distal or proximal wrist portion.

As is described below with respect to particular embodiments, shaped contact surfaces may be included such that nonattached rolling contact may permit pivoting of the adjacent disks, while balancing the amount of cable motion on opposite sides of the disks. In addition, the nonattached contact aspect of the these exemplary embodiments promotes convenient, simplified manufacturing and assembly processes and reduced part count, which is particularly useful in embodiments having a small overall wrist diameter.

It is to be understood that alternative embodiments having aspects of the invention may have one or more adjacent disks pivotally attached to one another and/or to a distal or proximal wrist portion in the same or substantially similar configurations by employing one or more fastener devices such as pins, rivets, bushings and the like.

Additional embodiments are described which achieve a cable-balancing configuration by inclusion of one or more inter-disk struts having radial plugs which engage the adjacent disks (or disk and adjacent proximal or distal wrist portion). Alternative configurations of the intermediate strut and radial plugs may provide a nonattached connection or an attached connection.

In certain embodiments, some of the cables are distal cables that extend from a proximal disk through at least one intermediate disk to a terminal connection to a distal disk. The remaining cables are medial cables that extend from the proximal disk to a terminal connection to a middle disk. The cables are actuated by a cable actuator assembly arranged to move each cable so as to deflect the wrist mechanism. In one exemplary embodiment, the cable actuator assembly may include a gimbaled cable actuator plate. The actuator plate includes a plurality of small radius holes or grooves for receiving the medial cables and a plurality of large radius holes or grooves for receiving the distal cables. The holes or grooves restrain the medial cables to a small radius of motion (e.g., ½ R) and the distal cables to a large radius of motion (R), so that the medial cables to the medial disk move a smaller distance (e.g., only half as far) compared to the distal cables to the distal disk, for a given gimbal motion or rotation relative to the particular cable. Note that for alternative embodiments having more than one intermediate cable termination segment, the cable actuator may have a plurality of sets of holes at selected radii (e.g., R, ⅔R, and ⅓R). The wrist embodiments described are particularly suitable for robotic surgical systems, although they may be included in manually operated endoscopic tools.

Embodiments including a cable actuator assembly having aspects of the invention provide to the simultaneous actuation of a substantial plurality of cables, and provide for a predetermined proportionality of motion of a plurality of distinct cable sets. This capability is provided with a simple, inexpensive structure which avoids highly complex control mechanisms. As described further below, for a given total cross-sectional area in each cable set and a given overall disk diameter, a mechanically redundant number of cables permits the cable diameter to be smaller, permits increasing the moment arm or mechanical advantage of the cables, and permits a larger unobstructed longitudinal center lumen along the centerline of the disks. These advantages are particularly useful in wrist members built to achieve the very small overall diameter such as are currently used in endoscopic surgery.

In some embodiments, a grip actuation mechanism is provided for operating a gripping end effector. When cables are used to manipulate the end effector, the grip actuation mechanism may include a grip cable actuator disposed in a tool or instrument proximal base or "back end." The path length of a grip actuation cable may tend to vary in length during bending of the wrist in the event that cable paths do not coincide with the neutral axis. The change in cable path lengths may be accounted for in the back end mechanism used to secure and control the cables. This may be achieved by including a cable tension regulating device in the grip actuation mechanism, so as to decouple the control of the end effector such as grip jaws from the bending of the wrist.

In specific embodiments, the back end mechanism is configured to allow for the replacement of the end effector, the wrist, and the shaft of the surgical instrument with relative ease.

In accordance with an aspect of the present invention, a minimally invasive surgical instrument comprises an elongate shaft having a working end, a proximal end, and a shaft axis between the working end and the proximal end. A wrist member has a proximal portion connected to the working end. An end effector is connected to a distal portion of the wrist member. The wrist member comprises at least three vertebrae connected in series between the working end of the elongate shaft and the end effector. The vertebrae include a proximal vertebra connected to the working end of the elongate shaft and a distal vertebra connected to the end effector.

Each vertebra is pivotable relative to an adjacent vertebra by a pivotal connection, which may employ a nonattached (or alternatively an attached) contact. At least one of the vertebrae is pivotable relative to an adjacent vertebra by a pitch contact around a pitch axis which is nonparallel to the shaft axis. At least one of the vertebrae is pivotable relative to an adjacent vertebra by another contact around a second axis which is nonparallel to the shaft axis and nonparallel to the pitch axis.

In accordance with another aspect of this invention, a minimally invasive surgical instrument comprises an elongate shaft having a working end, a proximal end, and a shaft axis between the working end and the proximal end. A wrist member has a proximal portion or proximal end member connected to the working end, and a distal portion or distal end member connected to an end effector. The wrist member comprises at least three vertebrae connected in series between the working end of the elongate shaft and an end effector.

The vertebrae include a proximal vertebra connected to the working end of the elongate shaft and a distal vertebra connected to the end effector. Each vertebra is pivotable relative to an adjacent vertebra by a pivotable vertebral joint. At least one of the vertebrae is pivotable relative to an adjacent vertebra by a pitch joint around a pitch axis which is nonparallel to the shaft axis. At least one of the vertebrae is pivotable relative to an adjacent vertebra by a yaw joint around a yaw axis which is nonparallel to the shaft axis and perpendicular to the pitch axis. An end effector is connected to a distal portion of the wrist member. A plurality of cables are coupled with the vertebrae to move the vertebrae relative to each other. The plurality of cables include at least one distal cable coupled with the terminating at the distal vertebra and extending proximally to a cable actuator member, and at least one intermediate cable coupled with and terminating at an intermediate vertebra disposed between the proximal vertebra and the distal vertebra and extending to the cable actuator member. The cable actuator member is configured to adjust positions of the vertebrae by moving the distal cable by a distal displacement and the intermediate cable by an intermediate displacement shorter than the distal displacement.

In some embodiments, a ratio of each intermediate displacement to the distal displacement is generally proportional to a ratio of a distance from the proximal vertebra to the intermediate vertebra to which the intermediate cable is connected and a distance from the proximal vertebra to the distal vertebra to which the distal cable is connected.

In accordance with another aspect of the invention, a method of performing minimally invasive endoscopic surgery in a body cavity of a patient comprises introducing an elongate shaft having a working end into the cavity. The elongate shaft has a proximal end and a shaft axis between the working end and the proximal end. A wrist member comprises at least three vertebrae connected in series between the working end of the elongate shaft and the end effector. The vertebrae include a proximal vertebra connected to the working end of the elongate shaft and a distal vertebra connected to the end effector. Each vertebra is pivotable relative to an adjacent vertebra by a pivotal coupling, which may employ a nonattached contact. An end effector is connected to a distal portion of the wrist member. The end effector is positioned by rotating the wrist member to pivot at least one vertebra relative to an adjacent vertebra by a pivotal pitch coupling around a pitch axis which is nonparallel to the shaft axis. The end effector is repositioned by rotating the wrist member to pivot at least one vertebra relative to an adjacent vertebra by another pivotal coupling around a second axis which is nonparallel to the shaft axis and nonparallel to the pitch axis.

In accordance with another aspect of the present invention, a minimally invasive surgical instrument has an end effector which comprises a grip support having a left pivot and a right pivot. A left jaw is rotatable around the left pivot of the grip support and a right jaw is rotatable around the right pivot of the grip support. A left slider pin is attached to the left jaw and spaced from the left pivot pin, and a right slider pin is attached to the right jaw and spaced from the right pivot pin. A slotted member includes a left slider pin slot in which the left slider pin is slidable to move the left jaw between an open position and a closed position, and a right slider pin slot in which the right slider pin is slidable to move the right jaw between an open position and a closed position. A slider pin actuator is movable relative to the slotted member to cause the left slider pin to slide in the left slider pin slot and the right slider pin to slide in the right slider pin slot, to move the left jaw and the right jaw between the open position and the closed position.

In accordance with another aspect of the present invention, a method of performing minimally invasive endoscopic surgery in a body cavity of a patient comprises providing a tool comprising an elongate shaft having a working end coupled with an end effector, a proximal end, and a shaft axis between the working end and the proximal end. The end effector includes a grip support having a left pivot and a right pivot; a left jaw rotatable around the left pivot of the grip support and a right jaw rotatable around the right pivot of the grip support, a left slider pin attached to the left jaw and spaced from the left pivot pin, a right slider pin attached to the right jaw and spaced from the right pivot pin; and a slotted member including a left slider pin slot in which the left slider pin is slidable to move the left jaw between an open position and a closed position, and a right slider pin slot in which the right slider pin is slidable to move the right jaw between an open position and a closed position. The method further comprises introducing the end effector into a surgical site; and moving the left slider pin to slide in the left slider pin slot and the right slider pin to slide in the right slider pin slot, to move the left jaw and the right jaw between the open position and the closed position.

According to another aspect, a medical instrument comprises a base shaft having a working end, a proximal end, and a shaft axis between the working end and the proximal end. A segmented wrist member comprises a plurality of spaced-apart segment vertebrae disposed sequentially adjacent to one another along a wrist longitudinal line. The plurality of vertebrae include a proximal vertebra connected to the shaft working end, a distal vertebra supporting an end effector, and at least one intermediate vertebra disposed between the proximal vertebra and the distal vertebra, the at least one intermediate vertebrae being connected to each adjacent vertebra by a pivotally movable segment coupling.

Each segment coupling has a coupling axis nonparallel to the wrist longitudinal line. At least two of the coupling axes are non-parallel to one another. At least one of the intermediate vertebrae is a medial vertebra. A plurality of movable tendon elements are disposed generally longitudinally with respect to the shaft and wrist member. The tendon elements each have a proximal portion, and have a distal portion connected to one of the distal vertebra and the medial vertebra so as to pivotally actuate the connected vertebra. At least one of the tendons is connected to the at least one medial vertebra and at least one of the tendons is connected to the distal vertebra. A tendon actuation mechanism is drivingly coupled to the tendons and configured to controllably move at least selected ones of the plurality of tendons so as to pivotally actuate the plurality of connected vertebrae to laterally bend the wrist member with respect to the shaft.

Another aspect is directed to a tendon actuating assembly for a surgical instrument, wherein the instrument includes a shaft-like member having a distal working end for insertion into a patient's body through an aperture, and wherein the working end includes at least one distal moveable member arranged to be actuated by at least one of a plurality of movable tendon element. The actuating assembly comprises a tendon actuator member which is configured to be movable to at least pivot in one degree of freedom, and which includes a plurality of tendon engagement portions. Each engagement portion is drivingly couplable to at least one of the plurality of tendons. A drive mechanism is drivingly coupled to the actuator member so as to controllably pivot the actuator member in the at least one degree of freedom, so as to move at least one of the tendons relative to the shaft-like member so as to actuate the distal moveable member.

In another aspect, a minimally invasive surgical instrument comprises a shaft having a working end, a proximal end, and a shaft axis between the working end and the proximal end. A segmented wrist member comprises a plurality of spaced-apart segment vertebrae disposed sequentially adjacent to one another along a wrist longitudinal line. The plurality of vertebrae include a proximal vertebra connected to the shaft working end, a distal vertebra supporting an end effector, and at least one intermediate vertebra disposed between the proximal vertebra and the distal vertebra. The at least one intermediate vertebrae is connected to each adjacent vertebra by a pivotally movable segment coupling. Each segment coupling has a coupling axis nonparallel to the wrist longitudinal line. At least two of the coupling axes are non-parallel to one another. The movable segment couplings include at least one spring-like element arranged to regulate the pivotal motion of at least one adjacent vertebra. A plurality of movable tendon elements are disposed generally longitudinally with respect to the shaft and wrist member. The tendon elements each have a proximal portion, and a distal portion connected to the distal vertebra so as to pivotally actuate the distal vertebra. A tendon actuation mechanism is drivingly coupled to the tendons and configured to controllably move at least one of the plurality of tendons so as to pivotally actuate the plurality of connected vertebrae to laterally bend the wrist member with respect to the shaft.

Another aspect is directed a segment pivoted coupling mechanism for pivotally coupling two adjacent segment vertebrae of a multi-segment flexible member of a medical instrument, wherein the two adjacent segments have bending direction with respect to one another, and wherein the flexible member has at least one neutral bending axis. The instrument includes at least two movable actuation tendon passing through at least two apertures in each adjacent vertebrae, wherein the at least two apertures in each of the vertebra are spaced apart on opposite sides of the neutral axis with respect to the pivot direction, and wherein openings of the apertures are disposed one adjacent surfaces of the two vertebrae so as to generally define an aperture plane. The coupling mechanism comprises at least one inter-vertebral engagement element coupled to each of the vertebrae, the element pivotally engaging the vertebrae so as to define at least two spaced-apart parallel cooperating pivot axes, each one of the pivot axes being aligned generally within the aperture plane of a respective one of the adjacent vertebra, so as to provide that each vertebra is pivotally movable about its respective pivot axis, so as to balance the motion of the tendons on opposite sides of the neutral axis when the flexible member is deflected in the bending direction.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an elevational view schematically illustrating the rotation of a gastroscope-style wrist;

FIG. **2** is an elevational view schematically illustrating an S-shape configuration of the gastroscope-style wrist of FIG. **1**;

FIG. **3** is an elevational view schematically illustrating a gastroscope-style wrist having vertebrae connected by springs in accordance with an embodiment of the present invention;

FIG. **4** is a partial cross-sectional view of a gastroscope-style wrist having vertebrae connected by wave springs according to an embodiment of the invention;

FIG. **5** is a perspective view of a positively positionable multi-disk (PPMD) wrist in pitch rotation according to an embodiment of the present invention;

FIG. **6** is a perspective view of the PPMD wrist of FIG. **5** in yaw rotation;

FIG. **7** is an elevational view of the PPMD wrist of FIG. **5** in a straight position;

FIG. **8** is an elevational view of the PPMD wrist of FIG. **5** in pitch rotation;

FIG. **9** is a perspective view of a PPMD wrist in a straight position according to another embodiment of the present invention;

FIG. **10** is a perspective view of the PPMD wrist of FIG. **9** in pitch rotation;

FIG. **11** is a perspective view of the PPMD wrist of FIG. **9** in yaw rotation;

FIG. **12** is an upper perspective of an intermediate disk in the PPMD wrist of FIG. **9**;

FIG. **13** is a lower perspective of the intermediate disk of FIG. **12**;

FIG. **14** is a perspective view of a PPMD wrist in pitch rotation in accordance with another embodiment of the present invention;

FIG. **15** is a perspective view of the PPMD wrist of FIG. **14** in yaw rotation;

FIG. **16** is a perspective view of a PPMD wrist in pitch rotation according to another embodiment of the present invention;

FIG. **17** is a perspective view of a PPMD wrist in a straight position in accordance with another embodiment of the present invention;

FIG. **18** is a perspective view of the PPMD wrist of FIG. **17** in pitch rotation;

FIG. **19** is an elevational view of the PPMD wrist of FIG. **17** in pitch rotation;

FIG. **20** is a perspective view of the PPMD wrist of FIG. **17** in yaw rotation;

FIG. **21** is an elevational view of the PPMD wrist of FIG. **17** in yaw rotation;

FIG. **22** is an elevational view of the PPMD wrist of FIG. **17** showing the actuation cables extending through the disks according to an embodiment of the invention;

FIG. **23** is an elevational view of the PPMD wrist of FIG. **17** in pitch rotation;

FIG. **24** is an elevational view of the PPMD wrist of FIG. **17** in yaw rotation;

FIG. **25** is an cross-sectional view of the coupling between the disks of the PPMD wrist of FIG. **17** illustrating the rolling contact therebetween;

FIG. **26** is a perspective view of a gimbaled cable actuator according to an embodiment of the invention;

FIG. **27** is a perspective view of a gimbaled cable actuator with the actuator links configured in pitch rotation according to another embodiment of the present invention;

FIG. **28** is a perspective view of the gimbaled cable actuator of FIG. **27** with the actuator links configured in yaw rotation;

FIG. **29** is another perspective view of the gimbaled cable actuator of FIG. **27** in pitch rotation;

FIG. **30** is a perspective view of the parallel linkage in the gimbaled cable actuator of FIG. **27** illustrating details of the actuator plate;

FIG. **31** is a perspective view of the parallel linkage of FIG. **30** illustrating the cover plate over the actuator plate;

FIG. **32** is another perspective view of the parallel linkage of FIG. **30** illustrating details of the actuator plate;

FIG. **33** is a perspective view of the parallel linkage of FIG. **30** illustrating the cover plate over the actuator plate and a mounting member around the actuator plate for mounting the actuator links;

FIG. **34** is a perspective view of the gimbaled cable actuator of FIG. **27** mounted on a lower housing member;

FIG. **35** is a perspective view of the gimbaled cable actuator of FIG. **27** mounted between a lower housing member and an upper housing member;

FIG. **36** is a perspective view of a surgical instrument according to an embodiment of the present invention;

FIG. **37** is a perspective view of the wrist and end effector of the surgical instrument of FIG. **36**;

FIG. **38** is a partially cut-out perspective view of the wrist and end effector of the surgical instrument of FIG. **36**;

FIGS. **38**A and **39** are additional partially cut-out perspective views of the wrist and end effector of the surgical instrument of FIG. **36**;

FIGS. **39**A and **39**B are plan views illustrating the opening and closing actuators for the end effector of the surgical instrument of FIG. **36**;

FIG. **39**C is a perspective view of an end effector according to another embodiment;

FIG. **40** is the perspective view of FIG. **39** illustrating wrist control cables;

FIG. **41** is an elevational view of the wrist and end effector of the surgical instrument of FIG. **36**;

FIG. **42** is a perspective view of a back end mechanism of the surgical instrument of FIG. **36** according to an embodiment of the present invention;

FIG. **43** is a perspective view of a lower member in the back end mechanism of FIG. **42** according to an embodiment of the present invention;

FIGS. **44-46** are perspective views of the back end mechanism according to another embodiment of the present invention;

FIG. **47** is a perspective view of a mechanism for securing the actuation cables in the back end of the surgical instrument of FIGS. **44-46** according to another embodiment of the present invention;

FIG. **48** is a perspective view of a back end mechanism of the surgical instrument of FIG. **36** according to another embodiment of the present invention;

FIG. **49** and **50** are perspective views of a back end mechanism of the surgical instrument of FIG. **36** according to another embodiment of the present invention;

FIG. **51** is a perspective of a PPMD wrist according to another embodiment;

FIG. **52** is an exploded view of a vertebra or disk segment in the PPMD wrist of FIG. **51**;

FIGS. **53** and **54** are elevational views of the PPMD wrist of FIG. **51**;

FIGS. **55** and **56** are perspective views illustrating the cable connections for the PPMD wrist of FIG. **51**;

FIGS. **57** and **58** are perspective views of a gimbaled cable actuator according to another embodiment;

FIG. **59** is a perspective view of the gimbal plate of the actuator of FIG. **55**;

FIGS. **60-62** are exploded perspective views of the gimbaled cable actuator of FIG. **55**;

FIG. **63** is another perspective view of the gimbaled cable actuator of FIG. **55**;

FIGS. **64-67** are perspective views of the back end according to another embodiment;

FIG. **68**A is an elevational view of a straight wrist according to another embodiment;

FIG. **68**B is an elevational view of a bent wrist; and

FIG. **68**C is a schematic view of a cable actuator plate according to another embodiment.

DETAILED DESCRIPTION OF THE INVENTION

As used herein, "end effector" refers to an actual working distal part that is manipulable by means of the wrist member for a medical function, e.g., for effecting a predetermined treatment of a target tissue. For instance, some end effectors have a single working member such as a scalpel, a blade, or an electrode. Other end effectors have a pair or plurality of working members such as forceps, graspers, scissors, or clip appliers, for example. In certain embodiments, the disks or vertebrae are configured to have openings which collectively define a longitudinal lumen or space along the wrist, providing a conduit for any one of a number of alternative elements or instrumentalities associated with the operation of an end effector. Examples include conductors for electrically activated end effectors (e.g., electrosurgical electrodes; transducers, sensors, and the like); conduits for fluids, gases or solids (e.g., for suction, insufflation, irrigation, treatment fluids, accessory introduction, biopsy extraction and the like); mechanical elements for actuating moving end effector members (e.g., cables, flexible elements or articulated elements for operating grips, forceps, scissors); wave guides; sonic conduction elements; fiberoptic elements; and the like. Such a longitudinal conduit may be provided with a liner, insulator or guide element such as a elastic polymer tube; spiral wire wound tube or the like.

As used herein, the terms "surgical instrument", "instrument", "surgical tool", or "tool" refer to a member having a working end which carries one or more end effectors to be introduced into a surgical site in a cavity of a patient, and is actuatable from outside the cavity to manipulate the end effector(s) for effecting a desired treatment or medical function of a target tissue in the surgical site. The instrument or tool typically includes a shaft carrying the end effector(s) at a distal end, and is preferably servomechanically actuated by a telesurgical system for performing functions such as holding or driving a needle, grasping a blood vessel, and dissecting tissue.

A. Gastroscope Style Wrist

A gastroscope style wrist has a plurality of vertebrae stacked one on top of another with alternating yaw (Y) and pitch (P) axes. For instance, an example of a gastroscope-style wrist may include twelve vertebrae. Such a wrist typically bends in a relatively long arc. The vertebrae are held together and manipulated by a plurality of cables. The use of four or more cables allows the angle of one end of the wrist to be determined when moved with respect to the other end of the wrist. Accessories can be conveniently delivered through the middle opening of the wrist. The wrist can be articulated to move continuously to have orientation in a wide range of angles (in roll, pitch, and yaw) with good control and no singularity.

FIGS. **1** and **2** show a typical prior art gastroscope style flexible wrist-like multi-segment member having a plurality of vertebrae or disks coupled in series in alternating yaw and pitch pivotal arrangement (YPYP . . . Y). FIG. **1** shows the rotation of a gastroscope-style wrist **40** having vertebrae **42**, preferably rotating at generally uniform angles between neighboring vertebrae **42**. On the other hand, when pitch and yaw forces are applied, the gastroscope-style wrist can take on an S shape with two arcs, as seen in FIG. **2**. In addition, backlash can be a problem when the angles between neighboring vertebrae vary widely along the stack. It may be seen that, in operation, the angles of yaw and pitch between adjacent segments may typically take a range of non-uniform, or indeterminate values during bending. Thus, a multi-segment wrist or flexible member may exhibit unpredictable or only partially controlled behavior in response to tendon actuation inputs. Among other things, this can reduce the bending precision, repeatability and useful strength of the flexible member.

One way to minimize backlash and avoid the S-shape configuration is to provide springs **54** between the vertebrae **52** of the wrist **50**, as schematically illustrated in FIG. **3**. The springs **54** help keep the angles between the vertebrae **52** relatively uniform during rotation of the stack to minimize backlash. The springs **54** also stiffen the wrist **50** and stabilize the rotation to avoid the S-shape configuration.

As shown in the wrist **60** of FIG. **4**, one type of spring that can be connected between the vertebrae **62** is a wave spring **64**, which has the feature of providing a high spring force at a low profile. FIG. **4** also shows an end effector in the form of a scissor or forcep mechanism **66**. Actuation members such as cables or pulleys for actuating the mechanism **66** may conveniently extend through the middle opening of the wrist **60**. The middle opening or lumen allows other items to be passed therethrough.

The wrist **60** is singularity free, and can be designed to bend as much as 360° if desired. The wrist **60** is versatile, and can be used for irrigation, imaging with either fiberoptics or the wires to a CCD passing through the lumen, and the like. The wrist **60** may be used as a delivery device with a working channel For instance, the surgical instrument with the wrist **60** can be positioned by the surgeon, and hand-operated catheter-style or gastroenterology instruments can be delivered to the surgical site through the working channel for biopsies.

Note that in FIGS. **1-4**, (and generally elsewhere herein) the distinction between yaw and pitch may be arbitrary as terms of generalized description of a multi-segment wrist or flexible member, the Y and P axes typically being generally perpendicular to a longitudinal centerline of the member and also typically generally perpendicular to each other. Note, however, that various alternative embodiments having aspects of the invention are feasible having Y and P axes which are not generally perpendicular to a centerline and/or not generally perpendicular to one another. Likewise, a simplified member may be useful while having only a single degree of freedom in bending motion (Y or P).

B. Positively Positionable Multi-Disk Wrist (PPMD Wrist)

A constant velocity or PPMD wrist also has a plurality of vertebrae or disks stacked one on top of another in a series of pivotally coupled engagements and manipulated by cables. In one five-disk embodiment (the disk count including end members), to prevent the S-shape configuration, one set of the cables (distal cables) extend to and terminate at the last vertebrae or distal end disk at the distal end of the wrist, while the remaining set of cables (medial cables) extend to and terminate at a middle disk. By terminating a medial set of cables at the medial disk, and terminating second distal set of cables at the distal disk, all pivotal degrees of freedom of the five disk sequence may be determinately controlled by cable actuators. There is no substantial uncertainty of wrist member shape or position for any given combination of cable actuations. This is the property implied by the term "positively positionable", and which eliminates the cause of S-curve bending or unpredictable bending as described above with respect to FIGS. **1-2**).

Note that medial cable set of the PPMD wrist will move a shorter distance than the distal set, for a given overall wrist motion (e.g., half as far). The cable actuator mechanism, examples of which are described further below, provides for this differential motion. Note also, that while the examples shown generally include a plurality of disks or segments which are similarly or identically sized, they need not be. Thus, where adjacent segments have different sizes, the scale of motion between the medial set(s) and the distal set may differ from the examples shown.

In certain preferred embodiments, one of a yaw (Y) or pitch (P) coupling is repeated in two consecutive segments. Thus, for the an exemplary sequence of four couplings between the 5 disk segments, the coupling sequence may be YPPY or PYYP, and medial segment disk (number **3** of **5**) is bounded by two Y or two P couplings. This arrangement has the property that permits a "constant velocity" rolling motion in a "roll, pitch, yaw" type instrument distal end. In other words, in the event that the instrument distal portion (shaft/wrist/end effector) is rotated axially about the centerline while the wrist is bent and while the end effector is maintained at a given location and pointing angle (analogous to the operation of a flexible-shaft screw driver), both end effector and instrument shaft will rotate at the same instantaneous angular velocity.

This property "constant velocity" may simplify control algorithms for a dexterous surgical manipulation instrument, and produce smoother operation characteristics. Note that this coupling sequence is quite distinct from the alternating YPYP . . . coupling arrangement of the prior art gastroscope style wrist shown in FIGS. **1** and **2**, which includes a strictly alternating sequence of yaw and pitch axes.

In an exemplary embodiment shown in FIGS. **5-8**, the wrist **70** has five disks **72-76** stacked with pitch, yaw, yaw, and pitch joints (the disk count including proximal and distal end member disks). The disks are annular and form a hollow center or lumen. Each disk has a plurality of apertures **78** for passing through actuation cables. To lower the forces on each cable, sixteen cables are used. Eight distal cables **80** extend to the fifth disk **76** at the distal end; and eight medial cables **82** extend to the third disk **74** in the middle. The number of cables may change in other embodiments, although a minimum of three cables (or four in a symmetrical arrangement), more desirably six or eight cables, are used. The number and size of cables are limited by the space available around the disks. In one embodiment, the inner diameter of each disk is about 3 mm, the outer diameter is about 2 mm, and the apertures for passing through the cables are about 0.5 mm in diameter. For a given total cross-sectional area in each cable set (medial or distal) and a given overall disk diameter, a mechanically redundant number of cables permits the cable diameter to be smaller, and thus permits the cables to terminate at apertures positioned farther outward radially from the center line of the medial or distal disk, thus increasing the moment arm or mechanical advantage of applied cable forces. In addition, the resulting smaller cable diameter permits a larger unobstructed longitudinal center lumen along the centerline of the disks. These advantages are particularly useful in wrist members built to achieve the very small overall diameter of the insertable instrument portion (about 5 mm or less) that is currently favored for the endoscopic surgery.

FIG. **5** shows alternating pairs of long or distal cables **80** and short or medial cable **82** disposed around the disks. The cables **80**, **82** extending through the disks are parallel to a wrist central axis or neutral axis **83** extending through the centers of the disks. The wrist neutral axis **83** is fixed in length during bending of the wrist **70**. When the disks are aligned in a straight line, the cables **80**, **82** are straight; when the disks are rotated during bending of the wrist **70**, the cables **80**, **82** bend with the wrist neutral axis. In the examples shown in FIGS. **5-8**, the disks are configured to roll on each other in nonattached, rolling contact to maintain the contact points between adjacent disks in the center, as formed by pairs of pins **86** coupled to apertures **78** disposed on opposite sides of the disks. The pins **86** are configured and sized such that they provide the full range of rotation between the disks and stay coupled to the apertures **78**. The apertures **78** may be replaced by slots for receiving the pins **86** in other embodiments. Note that the contour of pins **86** is preferably of a "gear tooth-like" profile, so as to make constant smooth contact with the perimeter **87** of its engaged aperture during disk rotation, so as to provide a smooth non-slip rolling engagement. FIGS. **5** and **8** show the wrist **70** in a 90° pitch position (by rotation of the two pitch joints), while FIG. **6** shows the wrist **70** in a 90° yaw position (by rotation of the two yaw joints). In FIG. **7**, the wrist **70** is in an upright or straight position. Of course, combined pitch and yaw bending of the wrist member can be achieved by rotation of the disks both in pitch and in yaw.

The wrist **70** is singularity free over a 180° range. The lumen formed by the annular disks can be used for isolation and for passing pull cables for grip. The force applied to the wrist **70** is limited by the strength of the cables. In one embodiment, a cable tension of about 15 lb. is needed for a yaw moment of about 0.25 N-m. Because there are only five disks, the grip mechanism needs to be able to bend sharply. Precision of the cable system depends on the friction of the cables rubbing on the apertures **78**. The cables **80**, **82** can be preloaded to remove backlash. Because wear is a concern, wear-resistant materials should desirably be selected for the wrist **70** and cables.

FIGS. **9-13** show an alternative embodiment of a wrist **90** having a different coupling mechanism between the disks **92-96** which include apertures **98** for passing through actuation cables. Instead of pins coupled with apertures, the disks are connected by a coupling between pairs of curved protrusions **100** and slots **102** disposed on opposite sides of the disks, as best seen in the disk **94** of FIGS. **12-13**. The other two intermediate disks **93**, **95** are similar to the middle disk **94**. The curved protrusions **100** are received by the curved slots **102** which support the protrusions **100** for rotational or rolling movement relative to the slots **102** to generate, for instance, the 90° pitch of the wrist **90** as shown in FIG. **10** and the 90° yaw of the wrist **90** as shown in FIG. **11**. FIG. **9** shows two distal cables **104** extending to and terminating at the distal disk **96**, and two medial cables **106** extending to and terminating at the middle disk **94**. Note that the example shown in FIGS. **9-13** is not a "constant velocity" YPPY arrangement, but may alternatively be so configured.

In another embodiment of the wrist **120** as shown in FIGS. **14** and **15**, the coupling between the disks **122-126** is formed by nonattached, rolling contact between matching gear teeth **130** disposed on opposite sides of the disks. The gear teeth **130** guide the disks in yaw and pitch rotations to produce, for instance, the 90° pitch of the wrist **120** as shown in FIG. **14** and the 90° yaw of the wrist **120** as shown in FIG. **15**.

In another embodiment of the wrist **140** as illustrated in FIG. **16**, the coupling mechanism between the disks includes apertured members **150**, **152** cooperating with one another to permit insertion of a fastener through the apertures to form a hinge mechanism. The hinge mechanisms disposed on opposite sides of the disks guide the disks in pitch and yaw rotations to produce, for instance, the 90° pitch of the wrist **140** as seen in FIG. **16**. Note that the example shown in FIG. **16** is not a "constant velocity" YPPY arrangement, but may alternatively be so configured.

FIGS. **17-24** show yet another embodiment of the wrist **160** having a different coupling mechanism between the disks **162-166**. The first or proximal disk **162** includes a pair of pitch protrusions **170** disposed on opposite sides about 180° apart. The second disk **163** includes a pair of matching pitch protrusions **172** coupled with the pair of pitch protrusions **170** on one side, and on the other side a pair of yaw protrusions **174** disposed about **90**° offset from the pitch protrusions **172**. The third or middle disk **164** includes a pair of matching yaw protrusions **176** coupled with the pair of yaw protrusions **174** on one side, and on the other side a pair of yaw protrusions **178** aligned with the pair of yaw protrusions **174**. The fourth disk **165** includes a pair of matching yaw protrusions **180** coupled with the pair of yaw protrusions **178** on one side, and on the other side a pair of pitch protrusions **182** disposed about **90**° offset from the yaw protrusions **180**. The fifth or distal disk **166** includes a pair of matching pitch protrusions **184** coupled with the pitch protrusions **182** of the fourth disk **165**.

The protrusions **172** and **176** having curved, convex rolling surfaces that make nonattached, rolling contact with each other to guide the disks in pitch or yaw rotations to produce, for instance, the 90° pitch of the wrist **160** as seen in FIGS. **18** and **19** and the 90° yaw of the wrist **160** as seen in FIGS. **20** and **21**. In the embodiment shown, the coupling between the protrusions is each formed by a pin **190** connected to a slot **192**.

FIGS. **22-24** illustrate the wrist **160** manipulated by actuation cables to achieve a straight position, a **90**° pitch position, and a 90° yaw position, respectively.

FIG. **25** illustrates the rolling contact between the curved rolling surfaces of protrusions **170**, **172** for disks **162**, **163**, which maintain contact at a rolling contact point **200**. The rolling action implies two virtual pivot points **202**, **204** on the two disks **162**, **163**, respectively. The relative rotation between the disks **162**, **163** is achieved by pulling cables **212**, **214**, **216**, **218**. Each pair of cables (**212**, **218**) and (**214**, **216**) are equidistant from the center line **220** that passes through the contact point **200** and the virtual pivot points **202**, **204**. Upon rotation of the disks **162**, **163**, the pulling cables shift to positions **212'**, **214'**, **216'**, **218'**, as shown in broken lines. The disk **162** has cable exit points **222** for the cables, and the disk **163** has cable exit points **224** for the cables. In a specific embodiment, the cable exit points **222** are coplanar with the virtual pivot point **202** of the disk **162**, and the cable exit points **224** are coplanar with the virtual pivot point **204** of the disk **164**. In this way, upon rotation of the disks **162**, **163**, each pair of cables (**212'**, **218'**) and (**214'**, **216'**) are kept equidistant from the center line **220**. As a result, the cable length paid out on one side is equal to the cable length pulled on the other side. Thus, the non-attached, rolling engagement contour arrangement shown in FIG. **25** may be referred to as a "cable balancing pivotal mechanism." This "cable balancing" property facilitates coupling of pairs of cables with minimal backlash. Note that the example of FIGS. **17-24** has this "cable balancing" property, although due to the size of these figures, the engagement rolling contours are shown at a small scale.

Optionally, and particularly in embodiments not employing a "cable balancing pivotal mechanism" to couple adjacent disks, the instrument cable actuator(s) may employ a cable tension regulation device to take up cable slack or backlash.

The above embodiments show five disks, but the number of disks may be increased to seven, nine, etc. For a seven-disk wrist, the range of rotation increases from 180° to 270°. Thus, in a seven-disk wrist, typically ⅓ of the cables terminate at disk **3**; ⅓ terminate at disk **5**; and ⅓ terminate at disk **7** (most distal).

C. Pivoted Plate Cable Actuator Mechanism

FIG. **26** shows an exemplary pivoted plate cable actuator mechanism **240** having aspects of the invention, for manipulating the cables, for instance, in the PPMD wrist **160** shown in FIGS. **17-21**. The actuator **240** includes a base **242** having a pair of gimbal ring supports **244** with pivots **245** for supporting a gimbal ring **246** for rotation, for example, in pitch. The ring **246** includes pivots **247** for supporting a rocker or actuator plate **250** in rotation, for example, in yaw. The actuator plate **250** includes sixteen holes **252** for passing through sixteen cables for manipulating the wrist **160** (from the proximal disk **162**, eight distal cables extend to the distal disk **166** and eight medial cables extend to the middle disk **164**).

The actuator plate **250** includes a central aperture **256** having a plurality of grooves for receiving the cables. There are eight small radius grooves **258** and eight large radius grooves **260** distributed in pairs around the central aperture **256**. The small radius grooves **258** receive medial cables that extend to the middle disk **164**, while the large radius grooves **260** receive distal cables that extend to the distal disk **166**. The large radius for grooves **260** is equal to about twice the small radius for grooves **258**. The cables are led to the rim of the central aperture **256** through the grooves **258**, **260** which restrain half of the cables to a small radius of motion and half of the cables to a large radius of motion, so that the medial cables to the medial disk **164** move only half as far as the distal cables to the distal disk **166**, for a given gimbal motion. The dual radius groove arrangement facilitates such motion and control of the cables when the actuator plate **250** is rotated in the gimbaled cable actuator **240**. A pair of set screws **266** are desirably provided to fix the cable attachment after pre-tensioning. The gimbaled cable actuator **240** acts as a master for manipulating and controlling movement of the slave PPMD wrist **160**. Various kinds of conventional actuator (not shown in FIG. **26**) may be coupled to actuator plate assembly to controllably tilt the plate in two degrees of freedom to actuate to cables.

FIGS. **27-35** illustrate another embodiment of a gimbaled cable actuator **300** for manipulating the cables to control movement of the PPMD wrist, in which an articulated parallel strut/ball joint assembly is employed to provide a "gimbaled" support for actuator plate **302** (i.e., the plate is supported so as to permit plate tilting in two DOF). The actuator **300** includes a rocker or actuator plate **302** mounted in a gimbal configuration. The actuator plate **302** is moved by a first actuator link **304** and a second actuator link **306** to produce pitch and yaw rotations. The actuator links **304**, **306** are rotatably coupled to a mounting member **308** disposed around the actuator plate **302**. As best seen in FIG. **33**, ball ends **310** are used for coupling the actuator links **304**, **306** with the mounting member **308** to form ball-in-socket joints in the specific embodiment shown, but other suitable rotational connections may be used in alternate embodiments. The actuator links **304**, **306** are driven to move generally longitudinally by first and second follower gear quadrants **314**, **316**, respectively, which are rotatably coupled with the actuator links **304**, **306** via pivot joints **318**, **320**, as shown in FIGS. **27** and **28**. The gear quadrants **314**, **316** are rotated by first and second drive gears **324**, **326**, respectively, which are in turn actuated by drive spools **334**, **336**, as best seen in FIGS. **34** and **35**.

The actuator plate **302** is coupled to a parallel linkage **340** as illustrated in FIGS. **30-33**. The parallel linkage **340** includes a pair of parallel links **342** coupled to a pair of parallel rings **344** which form a parallelogram in a plane during movement of the parallel linkage **340**. The pair of parallel links **342** are rotatably connected to the pair of parallel rings **344**, which are in turn rotatably connected to a parallel linkage housing **346** via pivots **348** to rotate in pitch. The pair of parallel links **342** may be coupled to the actuator plate **302** via ball-in-socket joints **349**, as best seen in FIG. **32**, although other suitable coupling mechanisms may be used in alternate embodiments.

FIGS. **27** and **29** show the actuator plate **302** of the gimbaled cable actuator **300** in pitch rotation with both actuator links **304**, **306** moving together so that the actuator plate **302** is constrained by the parallel linkage **340** to move in pitch rotation. In FIG. **28**, the first and second actuator links **304**, **306** move in opposite directions to produce a yaw rotation of the actuator plate **302**. Mixed pitch and yaw rotations result from adjusting the mixed movement of the actuator links **304**, **306**.

As best seen in FIGS. **30** and **32**, the actuator plate **302** includes eight small radius apertures **360** for receiving medial cables and eight large radius apertures **362** for receiving distal cables. FIG. **32** shows a medial cable **364** for illustrative purposes. The medial and distal actuation cables extend through the hollow center of the parallel linkage housing **346** and the hollow center of the shaft **370** (FIGS. **27** and **28**), for instance, to the middle and distal disks **164**, **166** of the PPMD wrist **160** of FIGS. **17-21**.

FIG. **34** shows the gimbaled cable actuator **300** mounted on a lower housing member **380**. FIG. **35** shows an upper housing member **382** mounted on the lower housing member **380**. The upper housing member **382** includes pivots **384** for rotatably mounting the gear quadrants **314**, **316**. A cover plate **390** may be mounted over the actuator plate **302** by fasteners **392**, as seen in FIGS. **27**, **28**, **31**, **33**, and **34**.

Note that the most distal disk (e.g., disk **166** in FIGS. **17-21**) may serve as a mounting base for various kinds of single-element and multi-element end effectors, such as scalpels, forceps, scissors, cautery tools, retractors, and the like. The central lumen internal to the disks may serve as a conduit for end-effector actuator elements (e.g., end effector actuator cables), and may also house fluid conduits (e.g., irrigation or suction) or electrical conductors.

Note that although gimbal ring support assembly **240** is shown in FIG. **26** for actuator plate **250**, and an articulated gimbal-like structure **300** is shown in FIGS. **27-35** for actuator plate **302**, alternative embodiments of the pivoted-plate cable actuator mechanism having aspects of the invention may have different structures and arrangements for supporting and controllably moving the actuator plate **250**. For example the plate may be supported and moved by various types of mechanisms and articulated linkages to permit at least tilting motion in two DOF, for example a Stewart platform and the like. The plate assembly may be controllably actuated by a variety of alternative drive mechanisms, such as motor-driven linkages, hydraulic actuators; electromechanical actuators, linear motors, magnetically coupled drives and the like.

D. Grip Actuation Mechanism

FIG. **36** shows a surgical instrument **400** having an elongate shaft **402** and a wrist-like mechanism **404** with an end effector **406** located at a working end of the shaft **402**. The wrist-like mechanism **404** shown is similar to the PPMD wrist **160** of FIGS. **17-21**. The PPMD wrist has a lot of small cavities and crevices. For maintaining sterility, a sheath **408**A may be placed over the wrist **404**. Alternatively, a sheath **408**B may be provided to cover the end effector **406** and the wrist **404**.

A back end or instrument manipulating mechanism **410** is located at an opposed end of the shaft **402**, and is arranged releasably to couple the instrument **400** to a robotic arm or system. The robotic arm is used to manipulate the back end mechanism **410** to operate the wrist-like mechanism **404** and the end effector **406**. Examples of such robotic systems are found in various related applications as listed above, such as PCT International Application No. PCT/US98/19508, entitled "Robotic Apparatus", filed on Sep. 18, 1998, and published as WO99/50721; and U.S. patent application Ser. No. 09/398,958, entitled "Surgical Tools for Use in Minimally Invasive Telesurgical Applications", filed on September **17**, **1999**. In some embodiments, the shaft **402** is rotatably coupled to the back end mechanism **410** to enable angular displacement of the shaft **402** relative to the back end mechanism **410** as indicated by arrows H.

The wrist-like mechanism **404** and end effector **406** are shown in greater detail in FIGS. **27-41**. The wrist-like mechanism **404** is similar to the PPMD wrist **160** of FIGS. **17-21**, and includes a first or proximal disk **412** connected to the distal end of the shaft **402**, a second disk **413**, a third or middle disk **414**, a fourth disk **415**, and a fifth or distal disk **416**. A grip support **420** is connected between the distal disk **416** and the end effector **406**, which includes a pair of working members or jaws **422**, **424**. To facilitate grip movement, the jaws **422**, **424** are rotatably supported by the grip support **420** to rotate around pivot pins **426**, **428**, respectively, as best seen in FIGS. **38-40**. Of course, other end effectors may be used. The jaws **422**, **424** shown are merely illustrative.

The grip movement is produced by a pair of slider pins **432**, **434** connected to the jaws **422**, **424**, respectively, an opening actuator **436**, and a closing actuator **438**, which are best seen in FIGS. **38-40**. The slider pins **432**, **434** are slidable in a pair of slots **442**, **444**, respectively, provided in the closing actuator **438**. When the slider pins **432**, **434** slide apart outward along the slots **442**, **444**, the jaws **422**, **424** open in rotation around the pivot pins **426**, **428**. When the slider pins **432**, **434** slide inward along the slots **442**, **444** toward one another, the jaws **422**, **424** close in rotation around the pivot pins **426**, **428**. The sliding movement of the slider pins **432**, **434** is generated by their contact with the opening actuator **436** as it moves relative to the closing actuator **438**. The opening actuator **436** acts as a cam on the slider pins **432**, **434**. The closing of the jaws **422**, **424** is produced by pulling the closing actuator **438** back toward the shaft **402** relative to the opening actuator **436** using a closing actuator cable **448**, as shown in FIG. **39**A. The opening of the jaws **422**, **424** is produced by pulling the opening actuator **436** back toward the shaft **402** relative to the closing actuator **438** using an opening actuator cable **446**, as shown in FIG. **39**B. The opening actuator cable **446** is typically crimped into the hollow tail of the opening actuator **436**, and the closing actuator cable **448** is typically crimped into the hollow tail of the closing actuator **438**. In a specific embodiment, the opening actuator cable **446** and the closing actuator cable **448** are moved in conjunction with one another, so that the opening actuator **436** and the closing actuator **438** move simultaneously at an equal rate, but in opposite directions. The actuation cables **446**, **448** are manipulated at the back end mechanism **410**, as described in more detail below. The closing actuator **438** is a slotted member and the closing actuator cable **446** may be referred to as the slotted member cable. The opening actuator **436** is a slider pin actuator and the opening actuator cable **448** may be referred to as the slider pin actuator cable.

To ensure that the grip members or jaws **422'**, **424'** move symmetrically, an interlocking tooth mechanism **449** may be employed, as illustrated in FIG. **39**C. The mechanism **449** includes a tooth provided on the proximal portion of one jaw **424'** rotatably coupled to a slot or groove provided in the proximal portion of the other jaw **424'**. The mechanism **449** includes another interlocking tooth and slot on the opposite side (not shown) of the jaws **422'**, **424'**.

A plurality of long or distal cables and a plurality of short or medial cables, similar to those shown in FIG. **5**, are used to manipulate the wrist **404**. FIG. **40** shows one distal cable **452** and one medial cable **454** for illustrative purposes. Each cable (**452**, **454**) extends through adjacent sets of apertures with free ends extending proximally through the tool shaft **402**, and makes two passes through the length of the wrist **404**. There are desirably a total of four distal cables and four medial cables alternatively arranged around the disks **412-416**.

The actuation cables **446**, **448** and the wrist control cables such as **452**, **454** pass through the lumen formed by the annular disks **412-416** back through the shaft **402** to the back end mechanism **410**, where these cables are manipulated. In some embodiments, a conduit **450** is provided in the lumen formed by the annular disks **412-416** (see FIG. **39**) to minimize or reduce cable snagging or the like. In a specific embodiment, the conduit **450** is formed by a coil spring connected between the proximal disk **412** and the distal disk **416**. The coil spring bends with the disks **412-416** without interfering with the movement of the disks **412-416**.

The grip support **420** may be fastened to the wrist **404** using any suitable method. In one embodiment, the grip support **420** is held tightly to the wrist **404** by support cables **462**, **464**, as illustrated in FIGS. **38** and **38**A. Each support cable extends through a pair of adjacent holes in the grip support **420** toward the wrist **404**. The support cables **462**, **464** also pass through the lumen formed by the annular disks **412-416** back through the shaft **402** to the back end mechanism **410**, where they are secured.

Referring to FIG. **41**, the wrist **404** has a wrist central axis or neutral axis **470** that is fixed in length during bending of the wrist **404**. The various cables, however, vary in length during bending of the wrist **404** as they take on cable paths that do not coincide with the neutral axis, such as the cable path **472** shown. Constraining the cables to bend substantially along the neutral axis **470** (e.g., by squeezing down the space in the wrist **404**) reduces the variation in cable lengths, but will tend to introduce excessive wear problems. In some embodiments, the change in cable lengths will be accounted for in the back end mechanism **410**, as described below.

FIGS. **42-46** show a back end mechanism **410** according to an embodiment of the present invention. One feature of this embodiment of the back end mechanism **410** is that it allows for the replacement of the end effector **406** (e.g., the working members or jaws **422**, **424**, the actuators **436**, **438**, and the actuation cables **446**, **448**) with relative ease.

As shown in FIG. **42**, the support cables **462**, **464** (see FIGS. **38** and **38**A) used to hold the grip support **420** to the wrist **404** extend through a central tube after passing through the shaft **402**. The support cables **462**, **464** are clamped to a lower arm **480** and lower clamp block **482** which are screwed tight. The lower arm **480** includes a pivot end **486** and a spring attachment end **488**. The pivot end **486** is rotatably mounted to the back end housing or structure **490**, as shown in FIG. **42**. The spring attachment end **488** is connected to a spring **492** which is fixed to the back end housing **490**. The spring **492** biases the lower arm **480** to apply tension to the support cables **462**, **464** to hold the grip support **420** tightly to the wrist **404**.

FIG. **43** shows another way to secure the support cables **462**, **464** by using four recesses or slots **484** in the lower arm **480** instead of the clamp block **482**. A sleeve is crimped onto each of the ends of the support cables **462**, **464**, and the sleeves are tucked into the recesses or slots **484**. This is done by pushing the lower arm **480** inward against the spring force, and slipping the sleeved cables into their slots.

FIG. **44** shows an additional mechanism that allows the lengths of the actuation cables **446**, **448** (see FIG. **39**) to change without affecting the position of the grip jaws **422**, **424**. The actuation cables **446**, **448** extending through the shaft **402** are clamped to a grip actuation pivoting shaft **500** at opposite sides of the actuation cable clamping member **502** with respect to the pivoting shaft **500**. The clamping member **502** rotates with the grip actuation pivoting shaft **500** so as to pull one actuation cable while simultaneously releasing the other to operate the jaws **422**, **424** of the end effector **406**.

Instead of the clamping member **502** for clamping the actuation cables **446**, **448**, a different cable securing member **502'** may be used for the grip actuation pivot shaft **500**, as shown in FIG. **47**. The cable securing member **502'** includes a pair of oppositely disposed recesses or slots **504**. A sleeve is crimped onto each of the ends of the actuation cables **446**, **448**, and the sleeves are tucked into the recesses or slots **504**. This is done by pushing the upper arm **530** inward against the spring force, and slipping the sleeved cables into their slots.

As shown in FIGS. **44-46**, the grip actuation pivot shaft **500** is controlled by a pair of control cables **506**, **508** that are connected to the motor input shaft **510**. The two control cables **506**, **508** are clamped to the grip actuation pivot shaft **500** by two hub clamps **512**, **514**, respectively. From the hub clamps **512**, **514**, the control cables **506**, **508** travel to two helical gear reduction idler pulleys **516**, **518**, and then to the motor input shaft **510**, where they are secured by two additional hub clamps **522**, **524**. As shown in FIG. **44**, the two control cables **506**, **508** are oppositely wound to provide the proper torque transfer in both clockwise and counterclockwise directions. Rotation of the motor input shaft **510** twists the grip actuation pivot shaft **500** via the control cables **506**, **508**, which in turn pulls one actuation cable while simultaneously releasing the other, thereby actuating the jaws **422**, **424** of the end effector **406**.

The grip actuation pivot shaft **500** and the pair of helical gear reduction idler pulleys **516**, **518** are pivotally supported by a link box **520**. The link box **520** is connected to a link beam **522**, which is pivotally supported along the axis of the motor input shaft **510** to allow the grip actuation pivot shaft **500** to move back and forth to account for change in cable length due to bending of the wrist **404**, without changing the relative position of the two actuation cables **446**, **448** that control the grip jaws **422**, **424**. This feature decouples the control of the grip jaws **422**, **424** from the bending of the wrist **404**.

FIGS. **45** and **46** show the addition of an upper arm **530** which is similar to the lower arm **480**. The upper arm **530** also has a pivot end **536** and a spring attachment end **538**. The pivot end **536** is rotatably mounted to the back end housing **490** along the same pivot axis as the pivot end **486** of the lower arm **480**. The upper arm **530** is connected to the grip actuation pivot shaft **500**. The spring attachment end **538** is connected to a spring **542** which is fixed to the back end housing **490**. The spring **542** biases the upper arm **530** to apply a pretension to the actuation cables **446**, **448**. The springs **492**, **542** are not shown in FIG. **46** for simplicity and clarity.

The configuration of the back end mechanism **410** facilitates relatively easy replacement of the actuators **436**, **438** and actuation cables **446**, **448**, as well as the working members or jaws **422**, **424**. The cables can be released from the back end mechanism **410** with relative ease, particularly when the cables are secured to recesses by crimped sleeves (see FIGS. **43**, **47**).

In another embodiment of the back end mechanism **410**A as shown in FIG. **48**, not only the end effector **406** but the wrist **404** and the shaft **402** may also be replaced with relative ease. As shown in FIGS. **27-35** and described above, the wrist cables (e.g., the distal cable **452** and medial cable **454** in FIG. **40**) for actuating the wrist **404** all terminate at the back end on a circular ring of the actuator plate **302**. The wrist cables are clamped to the actuator plate **302** with a cover plate **390** (see FIGS. **27-35**).

To achieve the replaceable scheme of the wrist **404** and shaft **402**, the wrist cables are fastened to a smaller plate (e.g., by clamping), and the smaller plate is fed from the instrument from the front **550** of the back end housing **490** and affixed to the actuator plate **302**.

In an alternate configuration, the actuator plate **302** may be repositioned to the front **550** of the back end housing **490** to eliminate the need to thread the smaller plate through the length of the shaft **402**.

FIGS. **49** and **50** show another back end mechanism **410**B illustrating another way of securing the cables. The support cables **462**, **464** (see FIGS. **38** and **38**A) are clamped to the arm **560** by a clamping block **562**. The arm **560** has a pivot end **564** and a spring attachment end **566**. The pivot end **564** is rotatably mounted to the back end housing or structure **490**. The spring attachment end **566** is connected to one or more springs **570** which are fixed to the back end housing **490**. The springs **570** bias the arm **560** to apply tension to the support cables **462**, **464** to hold the grip support **420** tightly to the wrist **404**.

The actuation cables **446**, **448** (see FIG. **39**) extend around pulleys **580** connected to the arm **560**, and terminate at a pair of hub clamps **582**, **584** provided along the motor input shaft **590**. This relatively simple arrangement achieves the accommodation of cable length changes and pretensioning of the cables. The support cables **462**, **464** are tensioned by the springs **570**. The actuation cables **446**, **448** are tensioned by applying a torque to the hub clamps **582**, **584**. The replacement of the end effector **406** and wrist **404** will be more difficult than some of the embodiments described above.

E. A More Compact Embodiment

FIGS. **51-67** illustrate another PPMD wrist tool that is designed to have certain components that are more compact or easier to manufacture or assemble. As shown in FIGS. **51-56**, the PPMD wrist **600** connected between a tool shaft **602** and an end effector **604**. The wrist **600** includes eight nested disk segments **611-618** that are preferably identical, which improves manufacturing efficiency and cost-effectiveness. An individual disk segment **610** is seen in FIG. **52**. Four struts **620** are provided, each of which is used to connect a pair of disk segments together. An individual strut **620** is shown in FIG. **52**.

The disk segment **610** includes a mating side having a plurality of mating extensions **622** extending in the axial direction (four mating extensions spaced around the circumference in a specific embodiment), and a pivoting side having a gear tooth **624** and a gear slot **626**. The gear tooth **624** and gear slot **626** are disposed on opposite sides relative to a center opening **628**. Twelve apertures **630** are distributed around the circumference of the disk segment **610** to receive cables for wrist actuation, as described in more detail below. The disk segment **610** further includes a pair of radial grooves or slots **632** disposed on opposite sides relative to the center opening **628**. In the specific embodiment shown, the radial grooves **632** are aligned with the gear tooth **624** and gear slot **626**.

The strut **620** includes a ring **634**, a pair of upper radial plugs or projections **636** disposed on opposite sides of the ring **634**, and a pair of lower radial plugs or projections **638** disposed on opposite sides of the ring **634**. The upper radial projections **636** and lower radial projections **638** are aligned with each other.

To assemble a pair of disk segments **610** with the strut **620**, the pair of lower radial projections **638** are inserted by sliding into the pair of radial grooves **632** of a lower disk segment. An upper disk segment is oriented in an opposite direction from the lower disk segment, so that the pivoting side with the gear tooth **624**, gear slot **626**, and radial grooves **632** faces toward the strut **620**. The pair of upper radial projections **638** of the strut **620** are inserted by sliding into the pair of radial grooves **632** of the upper disk segment. In the specific embodiment, the radial projections and radial grooves are circular cylindrical in shape to facilitate pivoting between the disk segments. The gear tooth **624** of the lower disk segment is aligned with the gear slot **626** of the upper disk segment to pivot relative thereto, while the gear tooth **624** of the upper disk segment is aligned with the gear slot **626** of the lower disk segment to pivot relative thereto. This is best seen in FIG. **51**. The movement between the gear tooth **624** and gear slot **626** is made by another nonattached contact.

The proximal or first disk segment **611** is connected to the end of the tool shaft **602** by the mating extensions **622** of the disk segment **611** and mating extensions **603** of the shaft **602**. The second disk segment **612** is oriented opposite from the first disk segment **611**, and is coupled to the first segment **611** by a strut **620**. The gear tooth **624** of the second disk segment **612** is engaged with the gear slot **626** of the first disk segment **611**, and the gear tooth **624** of the first disk segment **611** is engaged with the gear slot **626** of the second disk segment **612**. The third disk segment **613** is oriented opposite from the second disk segment **612**, with their mating sides facing one another and the mating extensions **622** mating with each other. The second disk segment **612** and the third disk segment **613** forms a whole disk. Similarly, the fourth disk segment **614** and fifth disk segment **615** form a whole disk, and the sixth disk segment **616** and the seventh disk segment **617** form another whole disk. The other three struts **620** are used to rotatably connect, respectively, third and fourth disk segments **613**, **614**; fifth and sixth disk segments **615**, **616**; and seventh and eighth disk segments **617**, **618**. The eighth or distal disk segment **618** is connected to the end effector **604** by the mating extensions **622** of the disk segment **618** and the mating extensions **605** of the end effector **604**.

As more clearly seen in FIG. **53**, the rotational coupling between the first disk segment **611** and second disk segment **612** provides pitch rotation **640** of typically about 45°, while the rotational coupling between the seventh disk segment **617** and eighth disk segment **618** provides additional pitch rotation **640** of typically about 45° for a total pitch of about 90°. The four disk segments in the middle are circumferentially offset by 90° to provide yaw rotation. As more clearly seen in FIG. **54**, the rotational coupling between the third disk segment **613** and fourth disk segment **614** provides yaw rotation **642** of typically about 45°, while the rotational coupling between the fifth disk segment **615** and sixth disk segment **161** provides additional yaw rotation **642** of typically about 45° for a total yaw of about 90°. Of course, different orientations of the disk segments may be formed in other embodiments to achieve different combinations of pitch and yaw rotation, and additional disk segments may be included to allow the wrist to rotate in pitch and yaw by greater than 90°.

Note that the rotatable engagement of the pair of projections **638** of each strut **620** with a respective bearing surface of grooves **632** on each adjacent disk portion **610** assures a "dual pivot point" motion of adjacent disks with respect to one another, such that the pivot points are in coplanar alignment with the cable apertures **630**. By this means, a "cable balancing" property is achieved, to substantially similar effect as is described above with respect to the embodiment of FIG. **25**. This assures that the cable length paid out on one side is equal to the cable length pulled on the other side of the disk.

The disk segments of the wrist **600** are manipulated by six cables **650** extending through the apertures **630** of the disk segments, as shown in FIGS. **55** and **56**. Each cable **650** passes through adjacent sets of apertures **630** to make two passes through the length of the wrist **600** in a manner similar to that shown in FIG. **40**, with the free ends extending through the tool shaft to the back end, where the cables are manipulated. The six cables include three long or distal cables and three short or medial cables that are alternately arranged around the disk segments. An internal lumen tube **654** may be provided through the center of the wrist **600** and extend through the interior of the tool shaft **602**, which is not shown in FIGS. **55** and **56**. In the embodiment shown, the cables **650** are crimped to hypotubes **656** provided inside the tool shaft **602**.

FIGS. **57-63** show a gimbal mechanism **700** in the back end of the tool. The gimbal mechanism **700** is more compact than the gimbal mechanism comprising the gimbal plate **302** and parallel linkage mechanism **340** of FIGS. **35-40**. The gimbal mechanism **700** includes another gimbal member or ring **702** that is mounted to rotate around an axis **704**. A gimbal plate or actuator plate **706** is mounted to the outer ring **700** to rotate around an orthogonal axis **708**. A lock plate **710** is placed over the gimbal plate **706**. As seen in FIG. **59**, the cables **650** from the wrist **600** are inserted through twelve cable holes **714**, **716** of the gimbal plate **706**, and pulled substantially straight back along arrow **716** toward the proximal end of the back end of the tool. The gimbal plate **706** includes six large radius apertures **714** for receiving distal cables **650**A and six small radius apertures **716** for receiving medial cables **650**B. The gimbal plate **706** has a first actuator connection **718** and a second actuator connection **719** for connecting to actuator links, as described below.

FIGS. **60** and **61** show the gimbal plate **706** and the lock plate **710** prior to assembly. The lock plate **710** is used to lock the cables **650**A, **650**B in place by moving wedges against the cables **650**. As best seen in FIG. **60**, the lock plate has three outward wedges **720** with radially outward facing wedge surfaces and three inward wedges **722** with radially inward facing wedge surface, which are alternately arranged around the lock plate **710**. The gimbal plate **706** has corresponding loose or movable wedges that mate with the fixed wedges **720**, **722** of the lock plate **710**. As best seen in FIG. **61**, the gimbal plate **706** includes three movable inward wedges **730** with radially inward facing wedge surfaces and curved outward surfaces **731**, and three movable outward wedges **732** with radially outward facing wedge surfaces and curved inward surface **733**. These movable wedges **730**, **732** are alternately arranged and inserted into slots provided circumferentially around the gimbal plate **706**.

The lock plate **710** is assembled with the gimbal plate **706** after the cables **650** are inserted through the cable holes **714**, **716** of the gimbal plate **706**. As the lock plate **710** is moved toward the gimbal plate **706**, the three outward wedges **720** of the lock plate **720** mate with the three movable inward wedges **730** in the slots of the gimbal plate **706** to push the movable inward wedges **730** radially outward against the six distal cables **650**A extending through the six large radius apertures **714**, which are captured between the curved outward surfaces **731** of the wedges **730** and the gimbal plate wall. The three inward wedges **722** of the lock plate **720** mate with the three movable outward wedges **732** in the slots of the gimbal plate **706** to push the movable outward wedges **732** radially inward against the six medial cables **650**B extending through the six small radius apertures **716**, which are captured between the curved inward surfaces **733** of the wedges **732** and the gimbal plate wall. As seen in FIGS. **62** and **63**, the lock plate **710** is attached to the gimbal plate **706** using fasteners **738** such as threaded bolts or the like, which may be inserted from the gimbal plate **706** into the lock plate **710**, or vice versa. In this embodiment of crimping all cables **650** by attaching the lock plate **710** to the gimbal plate **706**, the cable tension is not affected by the termination method.

The gimbaled cable actuator **800** incorporating the gimbal mechanism **700** as illustrated in the back end **801** FIGS. **64-67** is similar to the gimbaled cable actuator **300** of FIGS. **32-40**, but are rearranged and reconfigured to be more compact and efficient. The gimbaled cable actuator **800** is mounted on a lower housing member of the back end and the upper housing member is removed to show the internal details.

The gimbal plate **706** of the gimbal mechanism **700** is moved by a first actuator link **804** rotatably coupled to the first actuator connection **718** of the gimbal plate **706**, and a second actuator link **806** rotatably coupled to the second actuator connection **719** of the gimbal plate **706**, to produce pitch and yaw rotations. The rotatable coupling at the first actuator connection **718** and the second actuator connection **719** may be ball-in-socket connections. The actuator links **804**, **806** are driven to move generally longitudinally by first and second follower gear quadrants **814**, **816**, respectively, which are rotatably coupled with the actuator links **804**, **806** via pivot joints. The gear quadrants **814**, **816** are rotated by first and second drive gears **824**, **826**, respectively, which are in turn actuated by drive spools **834**, **836**. The gear quadrants **814**, **816** rotate around a common pivot axis **838**. The arrangement is more compact than that of FIGS. **32-40**. The first and second actuator links **804**, **806** move in opposite directions to produce a yaw rotation of the gimbal plate **706**, and move together in the same direction to produce a pitch rotation of the gimbal plate **706**. Mixed pitch and yaw rotations result from adjusting the mixed movement of the actuator links **804**, **806**. Helical drive gear **840** and follower gear **842** are used to produce row rotation for improved efficiency and cost-effectiveness.

The back end **801** structure of FIGS. **64-67** provides an alternate way of securing and tensioning the cables, including the support cables **462**, **464** for holding the grip support to the wrist (see FIGS. **38** and **38**A), and grip actuation cables **446**, **448** for actuating the opening and closing of the grip end effector (see FIG. **39**). The support cables **462**, **464** are clamped to an arm **860** which pivots around the pivot axis **838** and is biased by a cable tensioning spring **862**. The spring **862** biases the arm **860** to apply tension to the support cables **462**, **464** to hold the grip support tightly to the wrist (see FIGS. **38**, **38**A). The grip actuation cables **446**, **448** extend around pulleys **870** (FIG. **66**) connected to the spring-biased arm **860**, and terminate at a pair of hub clamps **866**, **868** provided along the motor input shaft **870**, as best seen in FIGS. **65** and **67**. The actuation cables **446**, **448** are tensioned by applying a torque to the hub clamps **866**, **868**.

FIGS. **68**A, **68**B, and **68**C illustrate schematically a PPMD wrist embodiment and corresponding actuator plate having aspects of the invention, wherein the wrist includes more than five segments or disks, and has more than one medial disk with cable termination. The PPMD wrist shown in this example has 7 disks (numbered 1-7 from proximal shaft end disk to distal end effector support disk), separated by 6 pivotal couplings in a P,YY,PP,Y configuration. Three exemplary cable paths are shown, for cable sets c**1**, c**2** and c**3**, which terminate at medial disks **3**, **5** and **7** respectively. FIG. **68**A shows the wrist in a straight conformation, and FIG. **68**B shows the wrist in a yaw-deflected or bent conformation. The wrist may similarly be deflected in pitch (into or out of page), or a combination of these. Except for the number of segments and cable sets, the wrist shown is generally similar to the embodiment shown in FIGS. **17-24**.

The wrist shown is of the type having at least a pair of generally parallel adjacent axes (e.g., . . . YPPY . . . or . . . PYYP . . .), but may alternatively be configured with a PY,PY,PY alternating perpendicular axes arrangement. Still further alternative embodiments may have combination configurations of inter-disk couplings, such as PYYP,YP and the like. The wrist illustrated has a constant segment length and sequentially repeated pivot axes orientations. In more general alternative exemplary embodiments, the "Y" and "P" axes need not be substantially perpendicular to each other and need not be substantially perpendicular to the centerline, and the sequential segments need not be of a constant length.

FIG. **68**C shows schematically the cable actuator plate layout, including cable set connections at r**1**, r**2** and r**3**, corresponding to cable sets c**1**, c**2** and c**3** respectively. Four connections are shown per cable set, but the number may be 3, and may be greater than 4.

In more general form, alternative PPMD wrist embodiment and corresponding actuator plates having aspects of the invention may be configured as follows: Where N represents the number of disk segments (including end disks), the number of cable termination medial disks M may be: M=(N−3)/2. The number of cable sets and corresponding actuator plate "lever arm" radii, including the distal cable set connections, is M+1.

In general, the "constant velocity" segment arrangement described previously is analogous to an even-numbered sequence of universal-joint-like coupling pairs disposed back-to-front and front-to-back in alternation. For example, a YP,PY or YP,PY,YP,PY segment coupling sequence provides the "constant velocity" property. Thus may be achieved for arrangements wherein N−1 is a multiple of four, such as N=5, 9 and the like.

It may be seen that, for a given angular defection per coupling, the overall deflection of the wrist increases with increasing segment number (the example of FIG. **68**B illustrates about 135 degrees of yaw).

The above-described arrangements of apparatus and methods are merely illustrative of applications of the principles of this invention and many other embodiments and modifications may be made without departing from the spirit and scope of the invention as defined in the claims. The scope of the invention should, therefore, be determined not with reference to the above description, but instead should be determined with reference to the appended claims along with their full scope of equivalents.

What is claimed is:

1. A medical apparatus comprising:

a tool shaft having a distal end, a proximal end, and a longitudinal axis extending from the distal end to the proximal end;

a wrist having a distal end and a proximal end, the wrist coupled at its proximal end to the distal end of the tool shaft, the wrist being articulable in pitch and in yaw;

an end effector coupled to the distal end of the wrist;

a frame coupled to the proximal end of the tool shaft;

a cable actuator mechanism coupled to the frame, the cable actuator mechanism configured to be movable relative to the frame; and

a plurality of transmission cables extending through the tool shaft from the cable actuator mechanism to the wrist, the plurality of transmission cables transmitting motion of the cable actuator mechanism to orient the end effector relative to the longitudinal axis of the tool shaft;

wherein the cable actuator mechanism comprises a gimbal assembly, the gimbal assembly configured to be pivotable relative to the frame about at least one axis.

2. The medical apparatus of claim **1**, wherein rotating the cable actuator mechanism about the longitudinal axis of the tool shaft rotates the tool shaft around the longitudinal axis of the tool shaft.

3. The medical apparatus of claim **1**, the plurality of transmission cables comprising a first cable coupled to a pitch axis pulley and a second cable coupled to a yaw axis pulley.

4. The medical apparatus of claim **1**, the wrist comprising a plurality of discrete disks.

5. The medical apparatus of claim **1**, the wrist comprising at least three disks in series between the distal end of the tool shaft and the end effector, the disks including a proximal disk coupled to the distal end of the tool shaft and a distal disk coupled to the end effector, each disk being pivotable relative to an adjacent disk, at least one of the disks being pivotable relative to an adjacent disk around a first axis that is nonparallel to the longitudinal axis, at least one of the disks being pivotable relative to an adjacent disk about a second axis that is nonparallel to the shaft axis and nonparallel to the first axis.

6. The medical apparatus of claim **1**, the wrist comprising a continuous flexible member having a plurality of segments with linkages positioned between adjacent segments.

7. The medical apparatus of claim **1**, wherein the wrist defines a plurality of lumens through which the plurality of transmission cables can movably pass.

8. The medical apparatus of claim **1**, wherein the wrist defines a central lumen configured to receive a drive element used to actuate the end effector.

9. The medical apparatus of claim **1**, the end effector comprising two elements movable between an open configuration and an approximated configuration, the medical apparatus further comprising at least one cable extending through the tool shaft to the end effector to actuate the end effector.

10. The medical apparatus of claim **9**, the end effector comprising scissors, shears, a needle driver, a dissector, a grasper, or a retractor.

11. The medical apparatus of claim **1**, wherein the tool shaft is insertable into a minimally invasive aperture on a human patient.

12. A medical apparatus comprising:

a tool shaft having a distal end, a proximal end, and a longitudinal axis extending from the distal end to the proximal end;

a wrist having a distal end and a proximal end, the wrist coupled at its proximal end to the distal end of the tool shaft, the wrist being articulable in pitch and in yaw;

an end effector coupled to the distal end of the wrist;

a frame coupled to the proximal end of the tool shaft;

a cable actuator mechanism coupled to the frame, the cable actuator mechanism configured to be movable relative to the frame; and

a plurality of transmission cables extending through the tool shaft from the cable actuator mechanism to the wrist, the plurality of transmission cables transmitting motion of the cable actuator mechanism to orient the end effector relative to the longitudinal axis of the tool shaft;

the cable actuator mechanism comprising:

a gimbal ring assembly; and

an actuating mechanism coupled to the gimbal ring assembly, wherein movement of the actuating mechanism moves the gimbal ring assembly relative to the frame.

13. A medical apparatus comprising:

a tool shaft having a distal end, a proximal end, and a longitudinal axis extending from the distal end to the proximal end;

a wrist having a distal end and a proximal end, the wrist coupled at its proximal end to the distal end of the tool shaft, the wrist being articulable in pitch and in yaw;

an end effector coupled to the distal end of the wrist;

a frame coupled to the proximal end of the tool shaft;

a cable actuator mechanism coupled to the frame, the cable actuator mechanism configured to be movable relative to the frame; and

a plurality of transmission cables extending through the tool shaft from the cable actuator mechanism to the wrist, the plurality of transmission cables transmitting motion of the cable actuator mechanism to orient the end effector relative to the longitudinal axis of the tool shaft;

the cable actuator mechanism comprising:

a mount;

an actuating plate coupled to the mount by linkages, wherein the actuating plate is movable relative to the mount; and

an actuating mechanism coupled to the actuating plate, wherein movement of the actuating mechanism moves the actuating plate relative to the frame.

14. The medical apparatus of claim **13**, the plurality of transmission cables being coupled to the actuating plate.

15. The medical apparatus of claim **13**, further comprising a plurality of actuator links coupled to the actuating plate via respective joints.

16. The medical apparatus of claim **15**, the joints comprising ball-and-socket joints.

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